

MASS, SALT, AND HEAT TRANSPORT ACROSS
SEVEN LATITUDE CIRCLES IN THE
NORTH ATLANTIC OCEAN:
A DESCRIPTION OF THE GENERAL CIRCULATION
BASED ON GEOSTROPHIC CALCULATIONS
FROM INTERNATIONAL GEOPHYSICAL
YEAR AND ADJACENT DATA

Timothy L. Baker

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Monterey, California



THESIS

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by

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section providing comprehensive temperature and salinity data extending from coast to coast and from the sea surface to the ocean floor.

Based on this level of no motion, net meridional heat transport values were determined for each latitude section and compared with those of previous studies for the North Atlantic Ocean and the Northern Hemisphere. The results of this comparison indicate that the inclusion of the heat transported in the bottom peripheral areas of the latitude sections did not affect the overall flux of heat to any appreciable degree when compared to results proposed by Jung (1974-1976) using the same data ignoring the bottom area. Also, it is seen that the meridional heat transport during the I.G.Y. was anomalously low when compared to values taken from 1955-1973.

Lastly, a general circulation pattern is developed from mass transport values for each of three layers of water: Upper Water, Intermediate Water, and Deep and Bottom Water. These circulation patterns are also compared with past descriptions of the general circulation; most notably, those of Sverdrup et al. (1942), Jung (1955), and Worthington (1976). The circulation patterns find good support with all three authors in the Upper and Intermediate Waters, but sharp contrasts exist between the deep and bottom circulation and that proposed by Worthington for his Deep Layer. Strong support for the pattern developed in this study is provided, however, by the works of Schmitz (1977), and Tucholke, Wright, and Hollister (1973).

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in the North Atlantic Ocean: A Description of the
General Circulation Based on Geostrophic Calculations
From International Geophysical Year and Adjacent Data

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ABSTRACT

This report using data from a five year period, including the International Geophysical Year (1954-1959), presents a detailed analysis of several aspects of the physical oceanography of the North Atlantic Ocean.

Assuming the geostrophic approximation to be valid, a level of no motion was established by satisfying the requirement of mass and salt continuity across seven latitude sections extending from 8°N to 48°N , with each latitude section providing comprehensive temperature and salinity data extending from coast to coast and from the sea surface to the ocean floor.

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I. INTRODUCTION

For centuries it has been recognized that the heat budget of the earth is characterized by a net surplus of solar radiation received in the tropics, and a net loss of heat in the polar regions. However, since the temperature regimes of these regions has not undergone a progressive change, it must be assumed that the excess heat received in the tropics is transported poleward by some mechanism(s) of energy transfer. Presumably the solid earth, via conduction, is not responsible for this transfer; therefore the atmosphere and world ocean - the earth's fluid envelope, must be the mechanism for this meridional transfer of energy. Originally it had been thought that the ocean was the principal vehicle of transfer; this idea was discarded in the early twentieth century in favor of the atmosphere being the dominant mode of energy transfer, with the oceanic contribution considered negligible.

In 1952 Jung proposed that the oceans, with their systems of currents, might be of far greater importance in the transfer of heat energy than had been considered. He pointed out that previous works such as that of Sverdrup (1942) had considered only the standing horizontal eddy, that is the Gulf Stream system and its return currents, in their calculations. Jung then proposed that closed vertical circulations in meridional planes conceivably could transport large quantities of energy, even though the velocities involved are quite small. This was followed by his detailed study in 1955 to determine the heat transported by geostrophic ocean currents in the North Atlantic Ocean using data from the Meteor Atlases.

Since that time many studies of the oceanic contribution to the meridional transfer of heat have been made (Budyko, 1956; Sverdrup, 1957; Bryan, 1962; Sellers, 1965; Vander Haar & Oort, 1973); but generally these studies have not used synoptic or nearly synoptic data for an entire ocean.

This study using a computer program developed by Greeson in his 1974 master's thesis, and seven nearly synoptic latitude sections of oceanographic data from the International Geophysical Year and adjacent years (1954-1959), was undertaken to determine the general geostrophic circulation and values of net heat flux for the North Atlantic Ocean.

II. BACKGROUND

A. ENERGY TRANSPORT

In dealing with energy transport within a fluid, be it the atmosphere or the ocean, we should begin with a general equation which applies to all fluid motion:

$$T^* = \int_S \left(\overset{(a)}{\rho U} + \overset{(b)}{\rho c^2/2} + \overset{(c)}{\rho \phi} + \overset{(d)}{P} \right) V_n dS \quad (1)$$

where T^* is the total meridional energy transferred normal to a vertical wall encircling the earth at a particular latitude, ρ is density, U is the internal energy per unit mass, c is the magnitude of the fluid velocity, ϕ is the potential energy per unit mass, P is pressure, V_n is the component of the fluid velocity normal to the latitude wall at a given level in either air or ocean and dS is the differential area of the wall.

This equation simply states that the total amount of energy transferred across a complete latitude circle is equal to the sum of the transport due to advection of internal energy (a), the transport of kinetic energy (b), the transport of potential energy (c), and rate of work done by pressure forces (d).

According to Jung (1952) the transport of kinetic energy (b) is negligible when compared to the other terms and can therefore be ignored.

Within the oceans, the transfer of energy is accomplished by the ocean currents. The simplifying assumption of geostrophic equilibrium usually is made to facilitate the determination of the magnitude of these currents. Also, the assumption of hydrostatic equilibrium in the vertical usually is

made, eliminating terms (c) and (d) from our general equation. Therefore, in the ocean, equation (1) reduces to :

$$T_o^* = \int_0 \rho_s U_s V_{ns} d0$$

where the subscript s stands for seawater, and 0 is that part of our latitude wall, S, cutting through the oceans. If we now neglect the compressibility effects in water we may write $U_s = C_{ps} T_s$ where C_{ps} is the specific heat at constant pressure of sea water and T_s is the temperature of sea water. Our equation now may be written:

$$T_o^* = \int_0 \rho_s C_{ps} T_s V_{ns} d0 \quad (2)$$

In the atmosphere certain simplifying assumptions also may be made. Term (d) of our general equation (1) may be replaced by $\rho_a RT_a$ where R is the gas constant for dry air (.287 joules $g^{-1} ^\circ K^{-1}$), T_a is the absolute temperature of air (the subscript a indicates air) if we assume the ideal gas law for the atmosphere (White, 1950). From term (a) we may write $U_a = C_{va} T_a + qL$, which states that the internal energy of the atmosphere is equal to the internal energy of dry air plus the latent energy contained in the water vapor. Here C_{va} is the specific heat at constant volume for dry air which may be considered a constant to a very good degree of approximation, q is the specific humidity, and L is the latent heat of condensation. Equation (1) now may be written as:

$$T_a^* = \int_a (C_{va} T_a + qL + \phi_a + RT_a) \rho_a V_{na} dA;$$

from the first law of thermodynamics for an isobaric process we have $C_{pa} = C_{va} + R$ (Haltner and Martin, 1957); therefore:

$$T_a^* = \int_a (C_{pa} T_a + qL + \phi_a) \rho_a V_{na} dA, \quad (3)$$

where A is that part of the latitude wall, S, which cuts through the atmosphere.

The determination of the total energy transport in the atmosphere - ocean complex now simply reduces to adding the advection of sensible heat of the atmosphere and oceans with the advection of water vapor and potential energy of the atmosphere. Therefore, the total transfer of energy is:

$$T^* = T_o^* + T_a^* = \int_o \rho_s C_{ps} T_s V_{ns} d\theta + \int_a (C_{pa} T_a + qL + \phi a) \rho_a V_{na} dA. \quad (4)$$

From the previous discussion it is obvious that the energy equilibrium maintained in both the polar and tropical regions is due to the meridional transport of sensible heat by the oceans and the transport of both sensible and latent heat by the atmosphere. However, the relative importance of the sea and air as mechanisms of energy transport has been a point of contention for many years and has only recently been satisfactorily resolved.

The debate over whether the atmosphere or the oceans are the dominant mechanisms of heat transport according to Jung (1956) began over a century ago when M. F. Maury (1856), in discussing the roles of each in maintaining the energy balance of the earth, expressed his belief that the oceans maintained the predominant role in heat transfer. Ferrel (1890) pointed out that although the volume exchange of air is greater than that of the sea, the mass exchange of the sea is greater between the tropics and poles than the air mass exchange. Ferrel further stated that the velocity of the air would need to be 2000 times that of the sea to allow the atmosphere to equal the heat transport of the sea.

Over the next thirty years with the advances in the theory of fluid motion together with improved instrumental and observational techniques, ideas about the relative importance of sea and air in transporting heat began to reverse. In 1925 Angstrom investigated Defant's "austausch" coefficients for the atmosphere and estimated that the oceans transported only as much heat poleward as the atmosphere. V. Bjerknes et al. (1933) felt that the contribution of the oceans was small compared to the energy transported by the air and therefore could be neglected. Sverdrup et al. (1942) stated that although the question had not been adequately studied, it was generally assumed that heat transport by ocean currents is negligible when dealing with averages for the entire earth, but in some regions it could be of considerable importance. In 1952 Jung hypothesized that the ocean's contribution might be greater than previously considered. This was followed by his detailed description of heat transport in the North Atlantic Ocean (Jung, 1955) which indicated that while the oceanic transport of sensible heat is less than the sensible and latent heat transported by the atmosphere, it is not negligible. This fact was reiterated by Neumann et al. (1966) when they stated that although the atmosphere is the principal mode of heat transport much of that heat transported is latent heat acquired from the oceans. Neumann further pointed out that if 4×10^{14} cal/sec of latent heat at 40°N were added to the sensible heat transported by the oceans the total would equal half of the total value required by radiation theory.

B. THE LEVEL OF NO MOTION

In utilizing the dynamical method of preparation of oceanographic data, we are faced with the problem of determining a reference level along

which the velocity is zero. This is necessary so that absolute current velocities may be found when the relative current velocities are referred to this level of no motion. Defant (1961) pointed out "The essential data needed to decide the position of the 'zero level' is largely lacking." We have seen a variety of indirect approaches developed which have tried to relate this level of no motion to some physical or chemical characteristic.

One of the earliest methods utilized was to place the reference level at a sufficiently great depth. This was based on the assumption that the deep waters of the oceans are uniform or nearly so and that in deep water the isopycnal and isobaric surfaces are nearly horizontal. Therefore the absolute current velocities could be found if the level of no motion were placed at a constant great depth.

A second school of oceanographers of which Jacobsen (1916) was the first, believed that the oxygen minimum in the oceans identified the level of minimum horizontal motion. The theory is based on the premise that the consumption of oxygen due to oxidation of organic matter by biological processes takes place at all levels; therefore the level of minimum oxygen content is found where the replenishment of oxygen by horizontal currents is a minimum. Rossby (1936) and Iselin (1936) pointed out that this approach would lead to odd results. This was aptly demonstrated by Dietrich (1936) who computed the magnitude of the Gulf Stream by the dynamic method, assuming the zero-level to be the oxygen minimum layer. His results indicated that the northward flow of the current was limited to the upper layers, while the counter current extended to the bottom with a transport of 78 Sverdrups (sv), twice that of the Gulf Stream.

Aside from these unreasonable results, the assumptions that the vertical distribution of organic matter is uniform and that oxygen consumption is

independent of the oxygen content in the water are incorrect. Therefore the level of no motion corresponding to the oxygen minimum appears unrealistic.

Parr (1938) developed a method for the determination of the layer of no motion in the oceans from the distortion of the thickness of isopycnal layers. This layer of constant density bounded by two isopycnal surfaces is called a pycnomere. According to Parr, the thickness of the pycnomere cannot remain constant in the presence of any current. Therefore, if the pycnomere is undistorted or if the distortion is minimal we must assume there is a complete lack of, or at least minimal water motion within the layer.

Fomin (1964) in analyzing Parr's method points out that the variation of current velocity in the vertical is a function not only of the slope of the isopycnal surfaces, but also, and more importantly, depends on the vertical water density gradient. He states that in areas of strong vertical density gradients the slope of isopycnal surfaces and the distortion of pycnomeres may be insignificant while current velocities vary greatly in the vertical. The converse also holds true. In areas of large slopes of isopycnal surfaces and considerable distortion of pycnomeres and weak density gradients, current velocity usually varies only slightly in the vertical. Therefore since Parr's method ignores the vertical density gradient, it is possible to pick as one's layer of no motion an undistorted pycnomere that is really a region of strong current velocity.

Hidaka developed two methods for the determination of the depth of the layer of no motion. The first method was based on determining the level from the salinity distribution. Hidaka (1949) proposed that the velocity field of the ocean current is constantly interacting with the

fields of the chemical and physical properties of sea water, resulting in a mutual adjustment if one field undergoes perturbation.

The differential equation of salinity distribution, s , in the oceans is:

$$\frac{ds}{dt} = k_1 \frac{\partial^2 s}{\partial x^2} + k_2 \frac{\partial^2 s}{\partial y^2} + k_3 \frac{\partial^2 s}{\partial z^2}$$

where t is time and k_1, k_2, k_3 are the turbulent diffusion coefficients in the x, y, z directions respectively. Hidaka now assumes $\frac{ds}{dt} = 0$ within the layer of no motion, and that $k_1 = k_2$ since the coefficient of horizontal diffusion does not depend on direction.

Depending on whether vertical or horizontal diffusion is dominant, and eliminating the small term(s), Hidaka reduces his equation to two equations which are used to determine the layer of no motion:

$$\frac{\partial^2 s}{\partial x^2} + \frac{\partial^2 s}{\partial y^2} = 0; \quad \frac{\partial^2 s}{\partial z^2} = 0$$

The first equation would be used in areas where horizontal salt diffusion is important, and the second in areas of vertical diffusion.

Fomin (1964) points out that recent evidence indicates that the coefficients of turbulent diffusion in the layer of no motion do not remain finite, as Hidaka asserts. Therefore the equations:

$$k_1 \frac{\partial^2 s}{\partial x^2} + k_1 \frac{\partial^2 s}{\partial y^2} = 0 \quad \text{and} \quad \frac{\partial^2 s}{\partial x^2} + \frac{\partial^2 s}{\partial y^2} = 0$$

do not follow one from the other. Thus, the solution to Hidaka's equations indicates the layer in which salinity is constant or varies linearly, or the depth of the boundaries of the intermediate salinity maximum. But these salinity characteristics have no definite relation to the current velocity field.

Hidaka's second method of determining the level of no motion utilizes the continuity equations and the computation of the vertical distribution of current velocity by the dynamic method. Hidaka's method utilizes a tetrahedral prism extending from the sea surface to the bottom. The apexes of the tetrahedron are oceanographic stations which have observed vertical temperature and salinity profiles. It is assumed that the exchange of salt and water volume takes place only through the lateral faces, and no exchange takes place through the ocean floor and sea surface. It is further assumed that the sum of the volume transport and salt mass transport across the lateral faces must equal zero.

In his method current velocities between stations relative to the current velocity C_i at the i^{th} level (such as the surface) are computed by the dynamic method. By this method, the magnitude of the absolute velocity $V(z)$ at depth z is:

$$V(z) = U(z) + C$$

where C is the current velocity at the sea surface and $U(z)$ is the current computed by the dynamic method relative to the sea surface. Substituting these values into his continuity equations he developed a deterministic set of six equations. Solving the system of equations he determined the surface gradient current velocity between the stations, which is used to determine the vertical distribution of the current velocity components normal to the prism faces.

Fomin (1964) points out that Hidaka's method cannot be used for practical computations since his simplification of the continuity equations is not theoretically correct and also because it leads to a set of equations that cannot be solved with the existing accuracy of measurements at sea.

Defant's (1941) method for the determination of the "zero" level is based on the analysis of differences in the dynamic depths of isobaric surfaces. By examining the dynamic height differences of isobaric surfaces of pairs of neighboring oceanographic stations in the Atlantic, Defant recognized a relatively thick layer whose depth varies uniformly in the horizontal direction while the change in the differences of the dynamic depths of isobaric surfaces was extremely small, amounting to only several dynamic millimeters (Fomin, 1964). Defant points out that the constancy of the differences in the dynamic depths indicates that the gradient component of the current velocity is constant in the vertical within the layer. Therefore, he assumes that this layer is motionless or nearly so and he considers it to be the layer directly adjoining the zero surface (Fomin, 1964).

The constancy in the differences of the dynamic depths of isobaric surfaces means that:

$$\Delta D_A = \Delta D_B$$

or

$$\left[\int_{P_n}^{P_{n+1}} \alpha dp \right]_A = \left[\int_{P_n}^{P_{n+1}} \alpha dp \right]_B ;$$

the differences in the depths between two levels, P_n and P_{n+1} , are equal at two adjacent oceanographic stations, A and B. In these equations ΔD_A and ΔD_B are increments of dynamic depth, and α is the specific volume of sea water.

To the present, Defant's method seems to be one of the most reasonable. However, when this method is used it must be understood that the current velocity is computed with low accuracy due to the accumulation of errors involved in the dynamic method. Therefore, in areas of low current

velocities this method may prove unusable since the computed D values will be comparable to the accumulated computational error.

The next method, and probably the most satisfactory, is that of Sverdrup et al. (1942). This method is based on the equation of continuity. The level of no motion is determined by comparing water mass transport computed by the dynamic method utilizing a horizontal reference surface. This reference surface will be the level of no motion when the net mass transport, in the oceanographic section of interest, above the reference surface is equal and opposite in direction to the net mass transport below this surface. This method has not been widely used because it requires that the data span an entire vertical cross section of the ocean.

Stommel (1956) developed a method for determining the level of no meridional motion based on Ekman's concept of the ocean consisting of a wind driven surface layer of frictional influence, and a deeper frictionless geostrophic layer. Basically the method states that at any position in the ocean the wind stress at the surface produces a net convergence or divergence of water. This water can escape or be introduced only through the bottom of the layer of frictional influence. Therefore the geostrophic layer will begin to stretch or shrink, and any water elements in this layer will stretch or shrink as they move poleward. This stretching and shrinking between the ocean bottom and the bottom of the frictional layer creates a vertical component of velocity which must, by mass conservation, equal the vertical velocity induced at the bottom of the frictional layer by the wind. This matching occurs only for a unique reference level, the level of no meridional motion.

Recently Stommel and Schott (1977) have indicated a new method based on the beta-spiral and the determination of the absolute velocity field from density data. This theory states that since the horizontal component

of velocity rotates with depth in the sea, absolute velocities can be obtained from observations of the density field alone. Assuming geostrophic flow, no flow across density surfaces, and a linear vorticity balance on a beta-plane, then:

$$w = uh_x + vh_y ; u_z = -\gamma h_{yz} ; v_z = h_{xz} ; \gamma = g/f ; fw_z = \beta v$$

where h is the height of a given density surface, the subscripts x, y, z , indicate derivatives, f is the coriolis parameter, and β is the derivative of f with respect to y . If we differentiate the first equation with respect to the vertical (z), and substitute from the remaining equations we have

$$uh_{xy} + v(h_y - \beta z/f)_z = 0.$$

Now, when the coefficient of u or v , h_{xy} or $(h_y - \beta z/f)_z$, vanishes at some depth without the other vanishing, that component of the absolute velocity also vanishes; and thereby establishes the "depth of no motion" for that component. Using the beta-spiral of the North Atlantic Ocean's subtropical gyre as a test of this technique, h_{xy} was found to vanish at approximately 900 meters, suggesting that v vanishes near that depth.

In this investigation the method proposed by Sverdrup et al. (1942) is used to determine the level of no motion, due to the comprehensive nature of the data involved and the belief that this method is the most reasonable so far proposed. However, as Jung (1955) emphasized "this problem of determining a level of no motion is still an open one which should be investigated in detail."

III. STATEMENT OF THE PROBLEM

To determine the heat energy transported by the North Atlantic Ocean we must possess comprehensive data concerning the thermal and salinity structure of the ocean, as well as a detailed understanding of the nature of the ocean circulation pattern.

We know that the energy transfer is accomplished by several processes: large-scale advection, smaller scale eddy diffusion, and molecular diffusion, as was pointed out by Sverdrup et al. (1942).

Large-scale advection is the dominant mode of transfer, with the contributions of eddy diffusion and molecular diffusion being several orders of magnitude smaller. Therefore eddy and molecular diffusion of energy have not been included in this study.

As shown earlier, the energy flux or transport across any latitude barrier in the ocean is expressed as:

$$T_o^* = \int_0 \rho_s C_{ps} T_s V_{ns} d0, \quad (2)$$

where the internal energy term or heat transport term, $C_{ps} T_s$ determines the total energy flux across a vertical cross section of area $d0$ within the ocean; we will assume that the specific heat at constant pressure of sea water, C_{ps} , has the value of unity. This introduces an insignificant error for the range of depths used in this study (Sverdrup et al. 1942, p. 62).

Velocities were computed utilizing the formula derived by Helland-Hansen and Sandstrom (1903) (Equation 5) and the procedure from Sverdrup et al. (1942) pp. 408-411; 447-448. Implicit in this procedure is the

assumption of geostrophic equilibrium within the oceans. This assumption of geostrophic balance, as was pointed out by Jung (1955), seems to be valid for large-scale motion outside the equatorial region, and is therefore applicable to this study.

Dynamic heights were determined and then were used to compute the geostrophic velocity differences between depths 1 and 2 in an area between adjacent pairs of oceanographic stations. The Helland-Hansen equation was used:

$$V_1 - V_2 = \frac{10C}{L} (D_A - D_B) , \quad (5)$$

where $C = 1/2 \Omega \sin \theta$, Ω is the earth's angular velocity, θ is the latitude, L is the horizontal distance between stations A and B, and D_A and D_B are the dynamic heights (or depths) of the two stations.

Prior to using this method the reference level or level of no motion must be established. The two criteria that must be met to determine this depth are zero net transport of both water mass and salt across the entire latitude sections of ocean, $\int_0 d\theta$:

$$\int_0 \rho_s V_{ns} d\theta = 0 \quad (6)$$

$$\int_0 \rho_s S V_{ns} d\theta = 0 \quad (7)$$

where in these equations S is salinity in parts per thousand.

In this study the mass balance was considered the primary criterion in determining the level of no motion (See Section V.B for explanation). Once the level of no motion was satisfactorily determined, a value for the heat flux across each latitude section was determined. A plot of integrated

mass transport for each pair of stations in three layers of water (Upper, Intermediate, and Deep and Bottom Water) also was made to determine the general circulation pattern for the three layers, with these circulation patterns directly responsible for the ocean heat transfer.

IV. PROCEDURE

A. DATA SOURCES

To undertake this study, extensive information on the temperature and salinity structure of the North Atlantic Ocean was needed as inputs for the dynamic method. The Atlantic Ocean Atlas (Fuglister, 1960) for the International Geophysical Year (1957-1958) was found to provide the most synoptic and comprehensive compendium of data for the North Atlantic Ocean made to this time. Seven of the eight east-west sections provided were utilized in this study. (The eighth section extended along the equator, a latitude at which the geostrophic assumption fails since the coriolis parameter goes to zero.) Table I provides information on these latitude cross-sections.

It is to be noted that all but the western-most stations of the 32°N section (North America-Bermuda), the 27°N section (Florida-Bahama Islands), and the entire 36°N latitude section occur between April and December of 1957. This fact is used as justification for the assumption that all data used are simultaneous. However it must be pointed out that this assumption is least justified in the western-most area of the ocean between the 32°N and 36°N sections where more than five years separate some of the observations.

Although these latitude sections provide considerable temperature and salinity data, there are areas in each section for which no data were obtained. These are the peripheral areas between the western-most stations and the American continent, between the eastern-most stations and Africa, Europe, or England, and the bottom area between the deepest observations of temperature and salinity and the ocean floor.

TABLE I

OCEANOGRAPHIC DATA: SHIPS, STATION NUMBERS, AND DATES

| <u>Latitude</u> | <u>Research Vessel</u> | <u>Station Numbers</u> | <u>Dates</u> |
|-----------------|------------------------|------------------------|---------------------|
| 8°N | Crawford | 154-184 | May 6-21, 1957 |
| 16°N | Crawford | 275-310 | Nov 13-29, 1957 |
| 24°N | Discovery II | 3587-3624 | Oct 6-28, 1957 |
| 27°N | Atlantis | 5343-5335 | Jun 27-28, 1955 |
| 32°N | Atlantis | 5203-5210 | Nov 11-16, 1954 |
| 32°N | Atlantis | 5292-5312 | Jun 9-14, 1955 |
| 32°N | Atlantis | 5564 | Apr 22, 1957 |
| 32°N | Discovery II | 3625-3650 | Nov 24-Dec 7, 1957 |
| 36°N | Chain | 17-77 | Apr 19-May 12, 1959 |
| 40°N | Crawford | 218-255 | Oct 2-22, 1957 |
| 48°N | Discovery II | 3509-3548 | Apr 16-27, 1957 |

To evaluate the significance of those areas not covered by data, results from the Cummings (1977) study of 8°N , 16°N , 24°N & 27°N , 32°N , 36°N , and 40°N were combined with information for 48°N . The results indicate that the nearshore holiday* areas amounted to less than one percent of the total area of interest (Table II). To see if the exclusion of these areas would seriously prejudice the results of this work, a study was made to estimate the transport of mass, salt, and heat in these peripheral areas. Temperature and salinity values were obtained from the U.S. Navy Fleet Numerical Weather Central's "Hydroclimatological Data Retrieval Program." These values combined with average monthly current values supplied by the appropriate "Pilot Chart of the North Atlantic Ocean" and an estimated average density value of 1.02395 gm/cm^3 obtained from the work of Greeson (1974), were used to compute the transport values. The results of this analysis (Appendix B) indicate that the transports were in fact low and would not greatly affect the overall net transport values since their inclusion would cause only minor variations in the level of no motion as was aptly demonstrated in Greeson's (1974) study of transports across 40°N latitude. These transport values for the peripheral areas were not, however, included in this study since the data involved varied by as much as twenty years from the period of interest.

*A holiday area is an area for which no data were available.

TABLE II

PERIPHERAL AREAS

| LATITUDE | AREAS IN KM ² SIDES | | EAST | AREA COVERED BY DATA | BOTTOM | TOTAL | AREA PERCENTAGES | | | |
|-----------|-----------------------------------|--|------|----------------------------|--------|--------|---------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------------|-------|
| | WEST | | | | | | $\frac{\text{DATA}}{\text{DATA+}} \frac{\text{DATA}}{\text{SIDES}}$ | $\frac{\text{DATA}}{\text{DATA+}} \frac{\text{DATA}}{\text{BOTTOM}}$ | $\frac{\text{DATA}}{\text{DATA+SIDES}} \frac{\text{DATA}}{\text{+BOTTOM}}$ | |
| 8°N | 2 | | 5 | 17,630 | 2,319 | 19,956 | 100% | 99.9% | 88.4% | 88.4% |
| 16°N | 0 | | 2 | 17,384 | 3,207 | 20,593 | 100% | 99.9% | 84.4% | 84.4% |
| 24°N+27°N | 5 | | 6 | 27,312 | 2,806 | 30,125 | 100% | 99.9% | 90.7% | 90.7% |
| 32°N | 6 | | 3 | 23,591 | 2,830 | 26,430 | 100% | 99.9% | 89.3% | 89.3% |
| 36°N | 6 | | 1 | 23,071 | 1,902 | 24,980 | 100% | 99.9% | 92.4% | 92.4% |
| 40°N | 33 | | 7 | 18,917 | 2,137 | 21,094 | 100% | 99.8% | 89.9% | 89.7% |
| 48°N | 23.5 | | 12.5 | 10,485 | 978 | 11,463 | 100% | 99.7% | 91.5% | 91.2% |

Values for 8°N, 16°N, 24°N+27°N, 32°N, 36°N, 40°N According to Cummings, 1977.

B. COMPUTATION OF VELOCITIES, TRANSPORT OF MASS, SALT CONTENT, AND HEAT

To date, actual synoptic velocity measurements have been made in only limited areas of the North Atlantic Ocean. Although this information is invaluable for limited area studies, it is not adequate for a study of this magnitude. However, with the assumption of geostrophic equilibrium, the I.G.Y. temperature and salinity data may be used with the procedure outlined by Sverdrup et al. (1942) (pp 408-411; 447-448) to determine dynamic height and synoptic velocity values for the areas of interest. To facilitate the numerous calculations involved, all computations were performed on an IBM-360/67 computer utilizing a program developed by Greeson (1974), which involves the following actual computational procedures.

The temperature and salinity data taken at various depths are first interpolated to standard depths. After the interpolated values are obtained, σ_t , the specific volume anomaly, and the specific volume are calculated for each standard depth. Then an average specific volume anomaly for each pair of standard depths for each station is computed by the following equation:

$$\bar{\delta} = \frac{\delta_z + \delta(z + \Delta z)}{2} \quad (8)$$

where $\bar{\delta}$ is the average specific volume anomaly, and δ_z and $\delta(z + \Delta z)$ are the specific volume anomalies at the standard depths of z and $z + \Delta z$.

The next step is to compute the dynamic heights, D , for each station. First, the dynamic height difference, ΔD , between the standard depths is computed by:

$$\Delta D = \bar{\delta} [z - (z + \Delta z)] \quad (9)$$

Then a summation of the dynamic height differences is made:

$$\sum_0^z \Delta D = D , \quad (10)$$

yielding the dynamic height of each oceanographic station. The distance between stations, L , which varies as a function of latitude and longitude, is then computed. Once L is known the relative velocity between pairs of stations for each standard depth is computed using the Helland-Hansen formula (5). From the relative velocities absolute geostrophic velocities can be derived by determining a level of no motion at which the absolute geostrophic velocity is zero.

Density is then computed for each observed salinity, temperature, and pressure by the equation:

$$\rho_{stp} = \frac{1}{\alpha_{stp}} \quad (11)$$

where α_{stp} is the specific volume for a particular salinity, temperature and pressure.

We now have available four values of temperature, salinity, velocity, and density corresponding to the four corners of a rectangle bounded by the two adjacent stations and by a pair of standard depths. These four values of each property then are averaged, yielding a single value for each rectangular area. The area of the rectangle is then determined by multiplying the station spacing, L , with the increment of depth, Δz .

By multiplying the area, the average density, and the average velocity it is possible to determine the mass transport for each rectangular area. This value in turn is multiplied by the average salinity and average absolute temperature to determine the salt flux and heat flux for each rectangular area.

These values then are summed vertically, yielding the net flux of mass, salt, and heat for that pair of stations. These values also are summed horizontally yielding the net flux for each pair of standard depths across the entire latitude section. These net horizontal values then are summed vertically giving the total net flux of mass, salt, and heat computed for the entire latitude section, minus the peripheral areas. This process is depicted in Figure 1.

The computer program utilized calculates the values of transport in the vertical only to the deepest standard depth common for a pair of stations. Therefore the transport value for the area between this deepest common depth and the ocean floor is not included in the net transport figures for each pair of stations. These areas are depicted in Figures 2 through 8 as the area between the bottom and the solid line.

To compute the transport values for these areas the bathymetric profile for each latitude section was first obtained. The oceanographic stations and the deepest common depths then were plotted, and the area between the ocean floor and the deepest common depth for each pair of stations was determined (the "bottom area" between the station pair). In these areas a linear decrease in velocity was assumed to exist between the absolute geostrophic velocity at the deepest common level and zero velocity at the ocean floor; therefore a value of one half the deepest calculated absolute velocity was used as the average velocity value for each area. This average velocity value was multiplied then by the deepest calculated density and by the bottom area to determine the mass transport across the bottom area for each pair of stations. This value in turn was multiplied by the deepest salinity and temperature values to determine the corresponding salt and heat transports. These transport estimates of mass, salt, and heat across the bottom area for each pair of stations then were summed

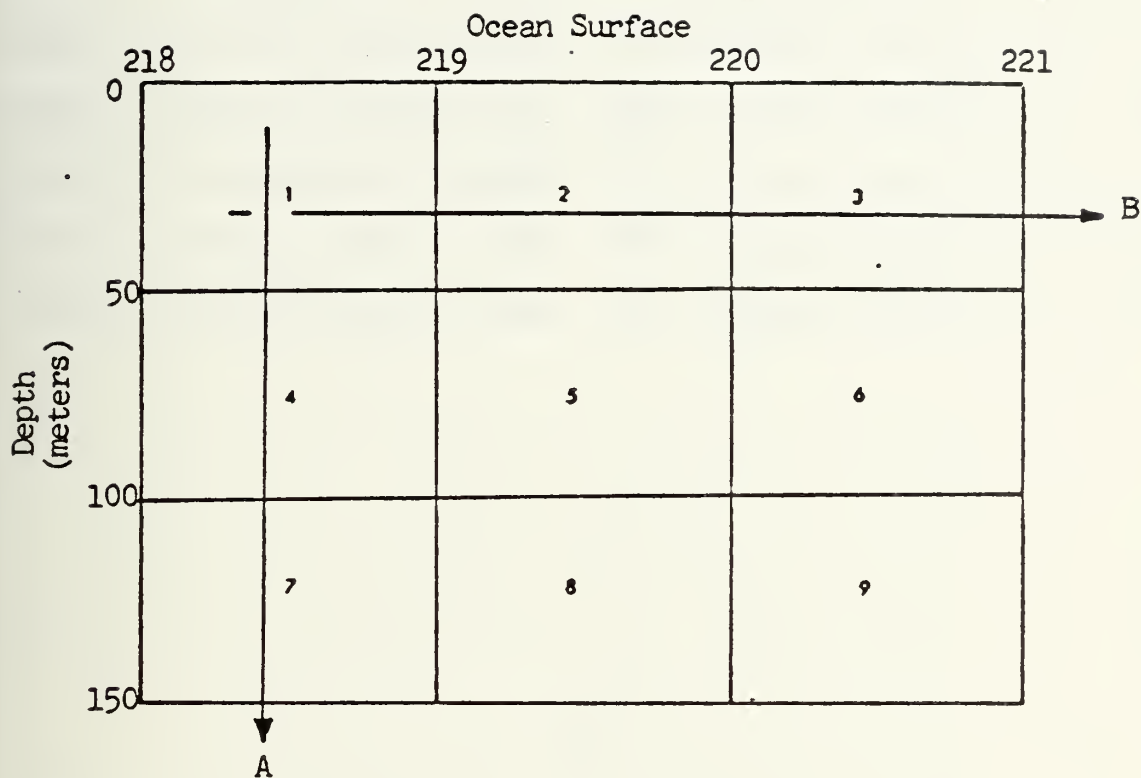


Figure 1. Illustration of the summation process performed in the computer program for a sample cross section of ocean. A represents integrated transport for a pair of stations 218-219. B represents the net transport for the layer 0 to 50m. According to Greeson (1974).

FIGURES 2-8

| | |
|-----------------------------------------------------------------|----|
| FIGURE 2 - Bottom peripheral areas: 8°N latitude section ----- | 35 |
| FIGURE 3 - Bottom peripheral areas: 16°N latitude section ----- | 36 |
| FIGURE 4 - Bottom peripheral areas: 24°N latitude section ----- | 37 |
| FIGURE 5 - Bottom peripheral areas: 32°N latitude section ----- | 38 |
| FIGURE 6 - Bottom peripheral areas: 36°N latitude section ----- | 39 |
| FIGURE 7 - Bottom peripheral areas: 40°N latitude section ----- | 40 |
| FIGURE 8 - Bottom peripheral areas: 48°N latitude section ----- | 41 |

8° NORTH

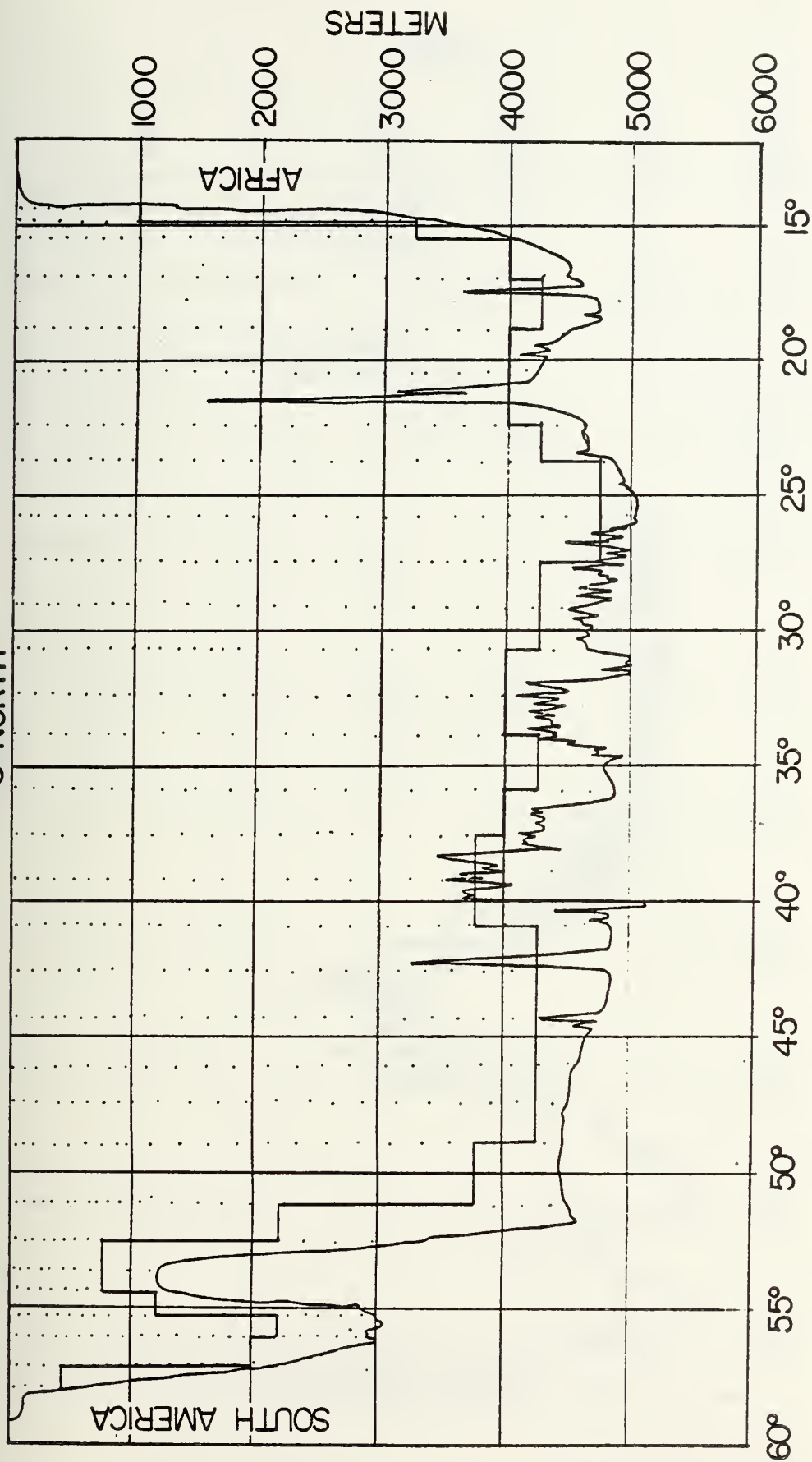


Figure 2

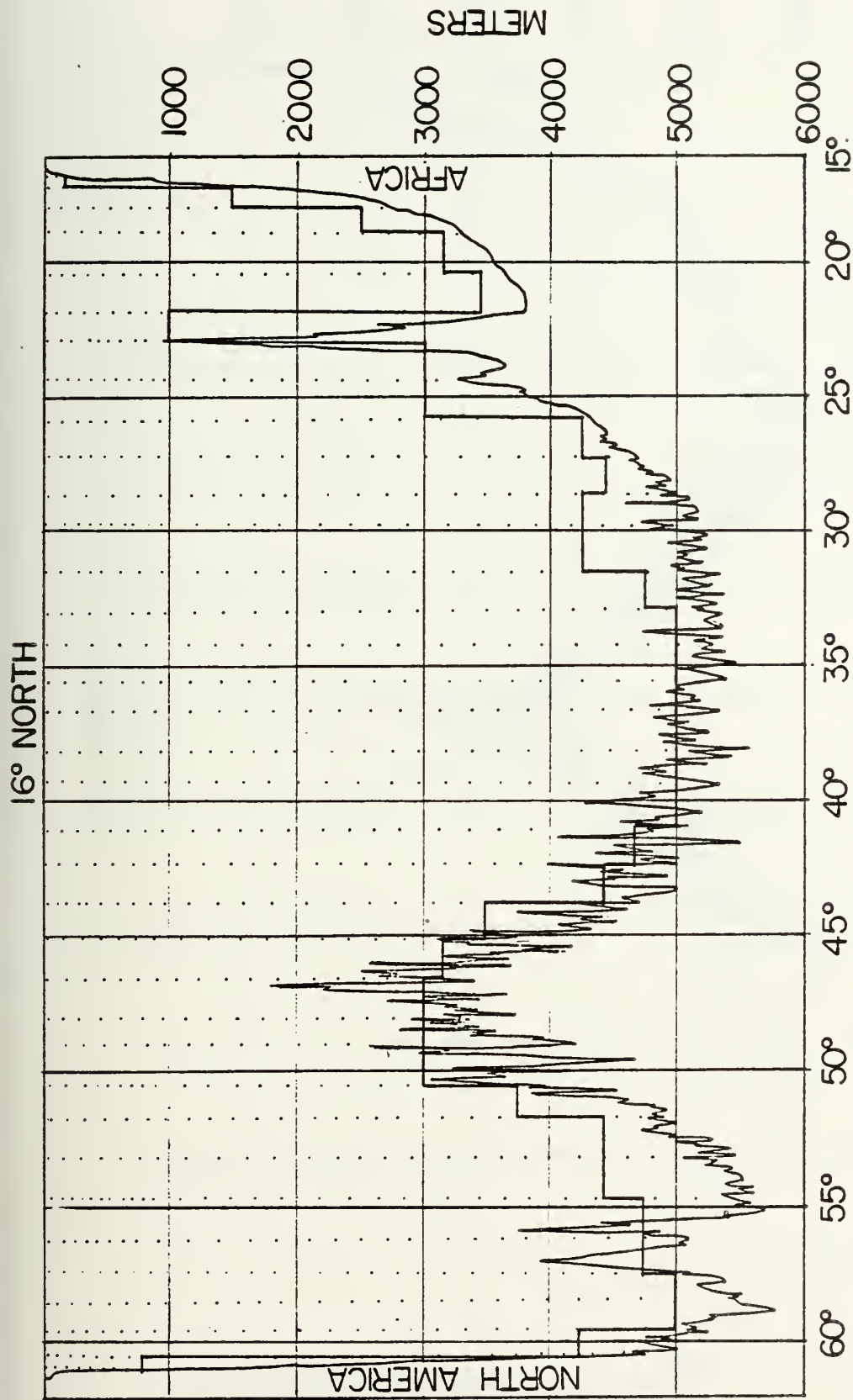


Figure 3

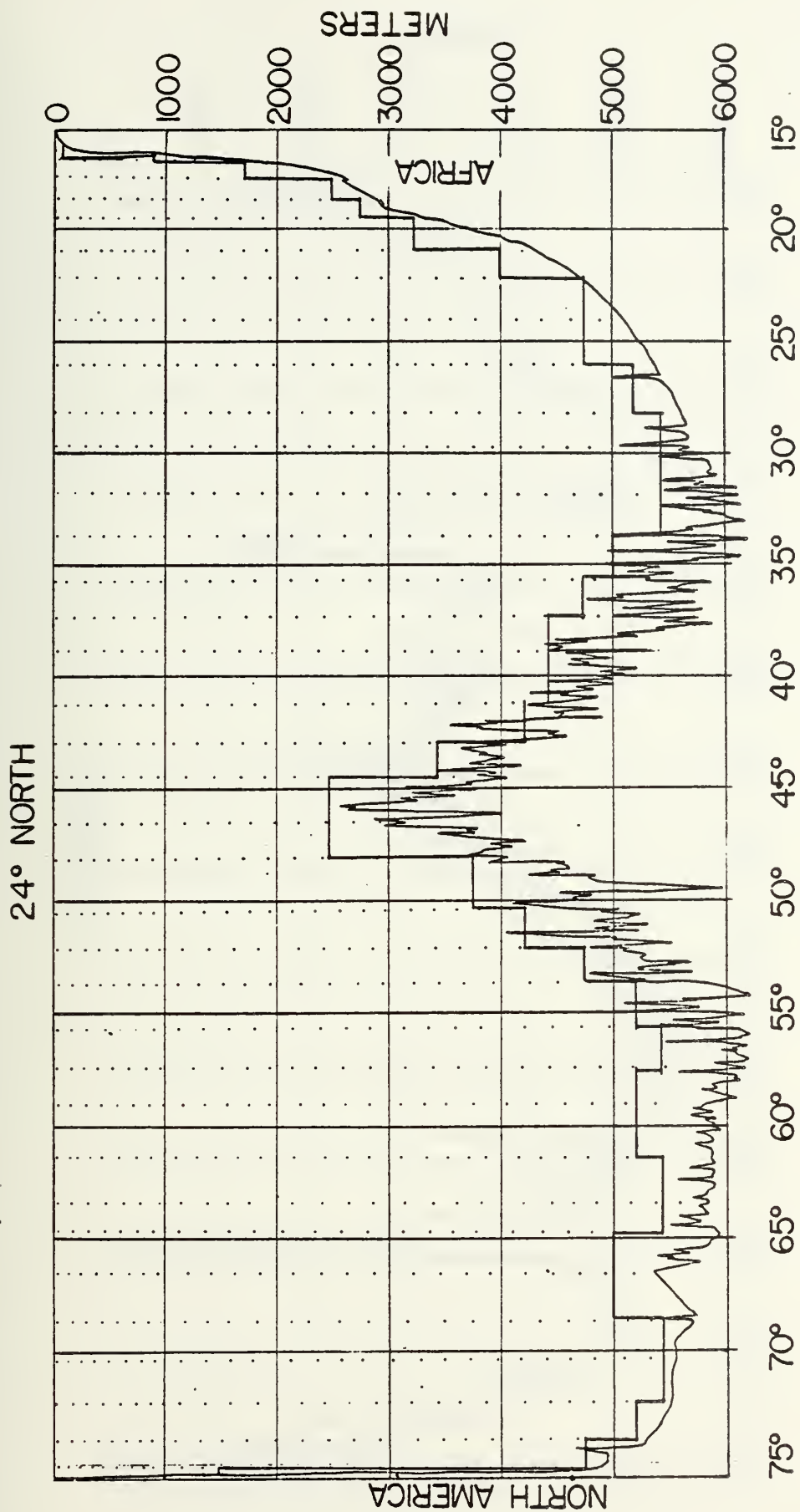


Figure 4

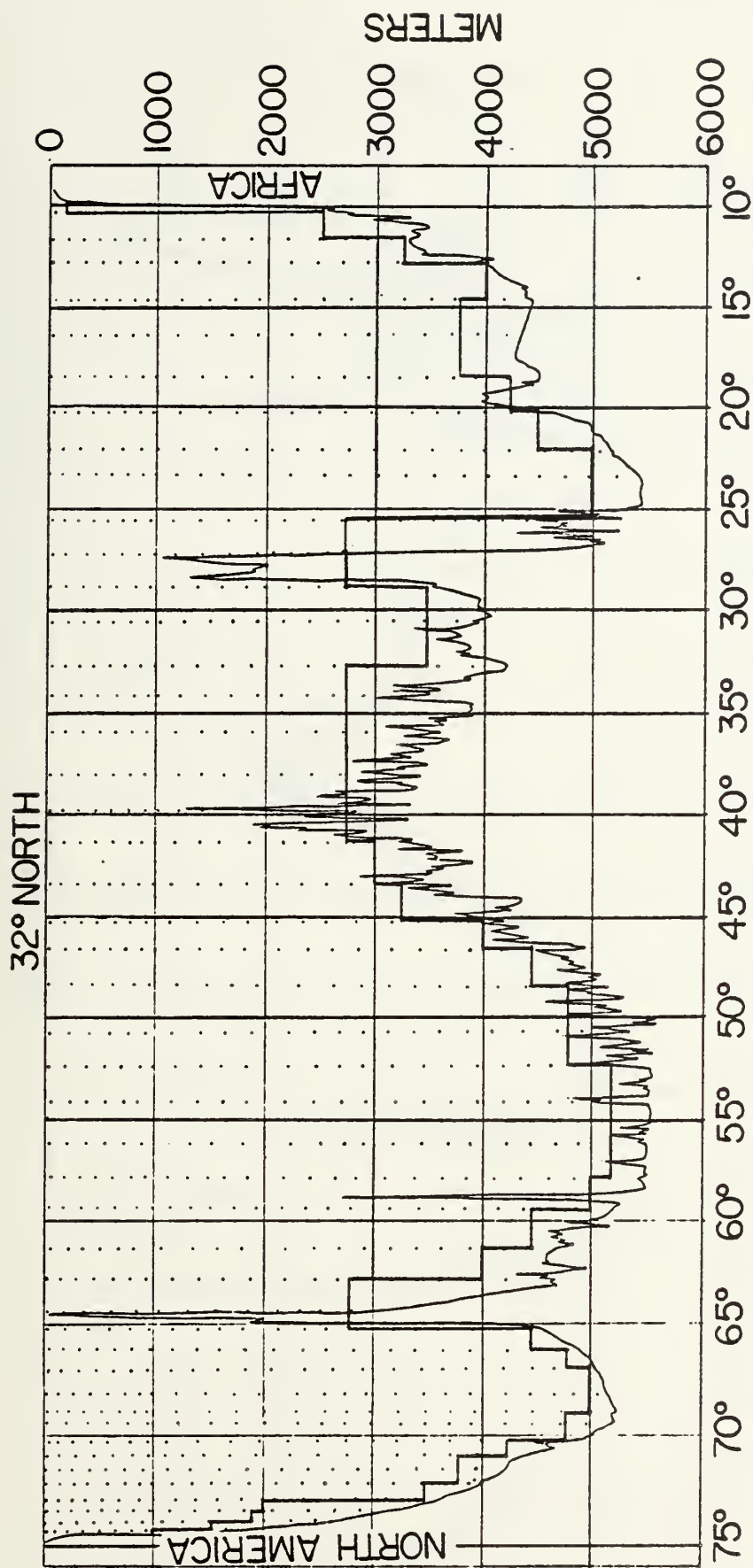


Figure 5

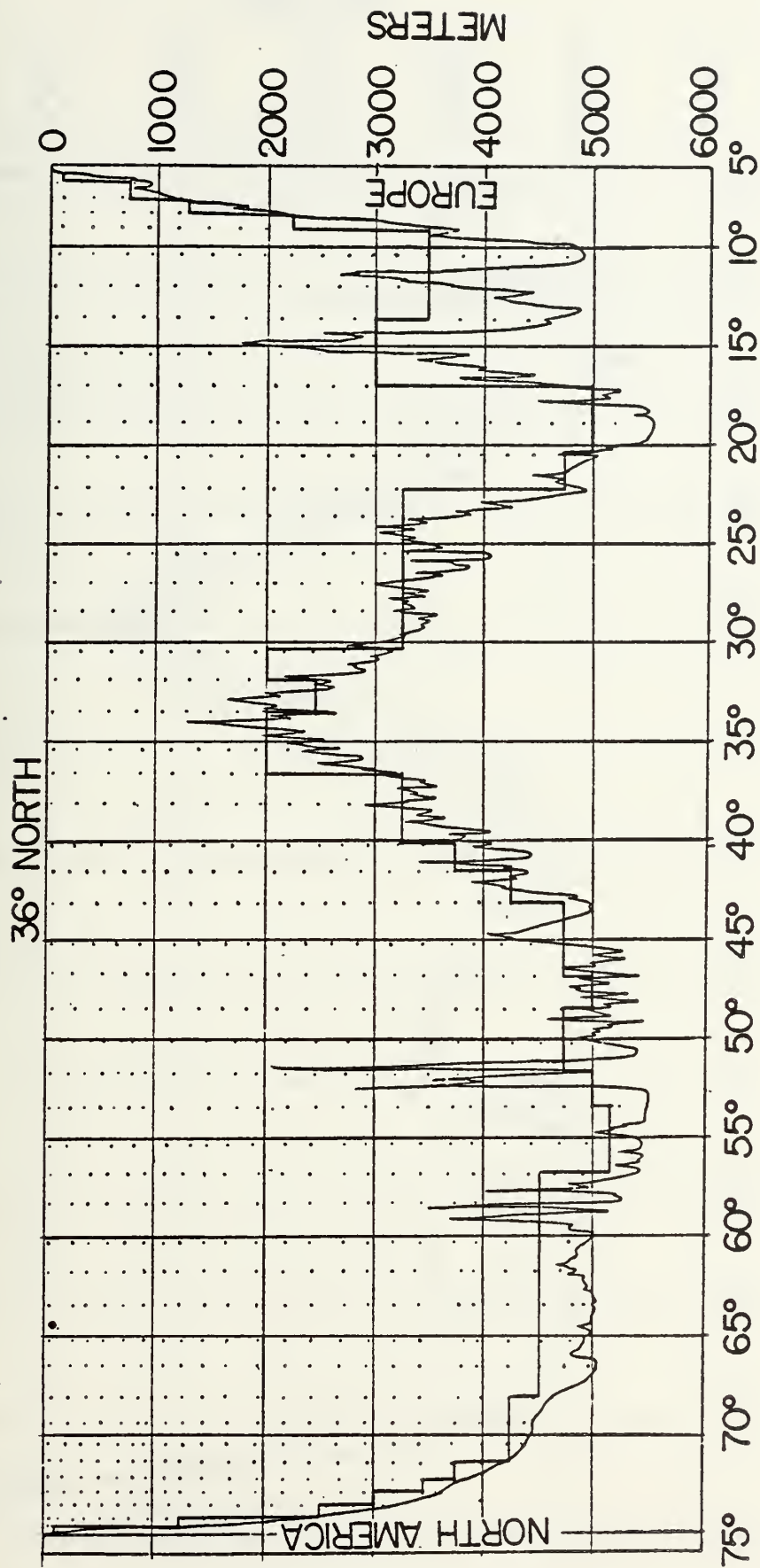


Figure 6

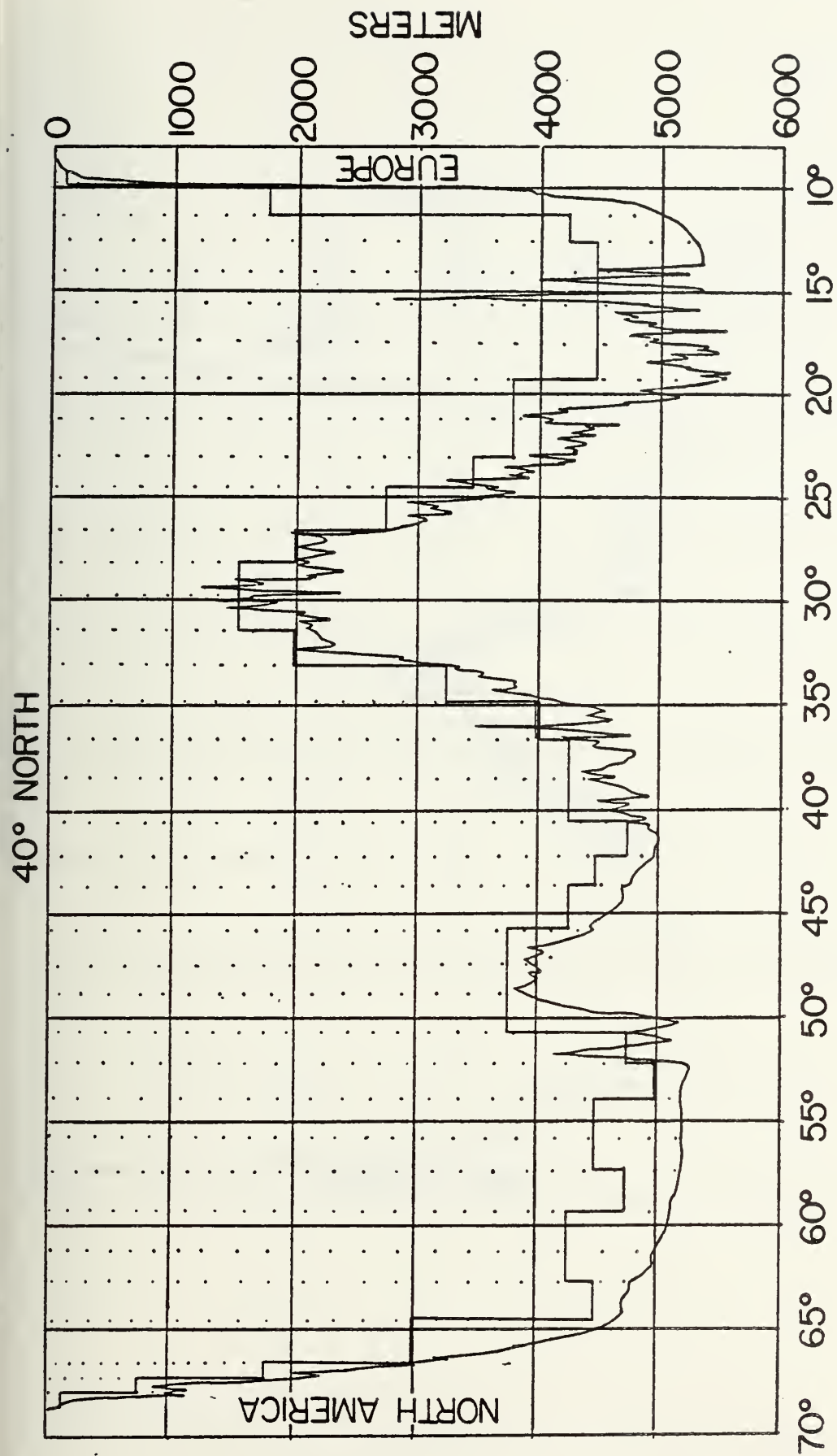


Figure 7

48° NORTH

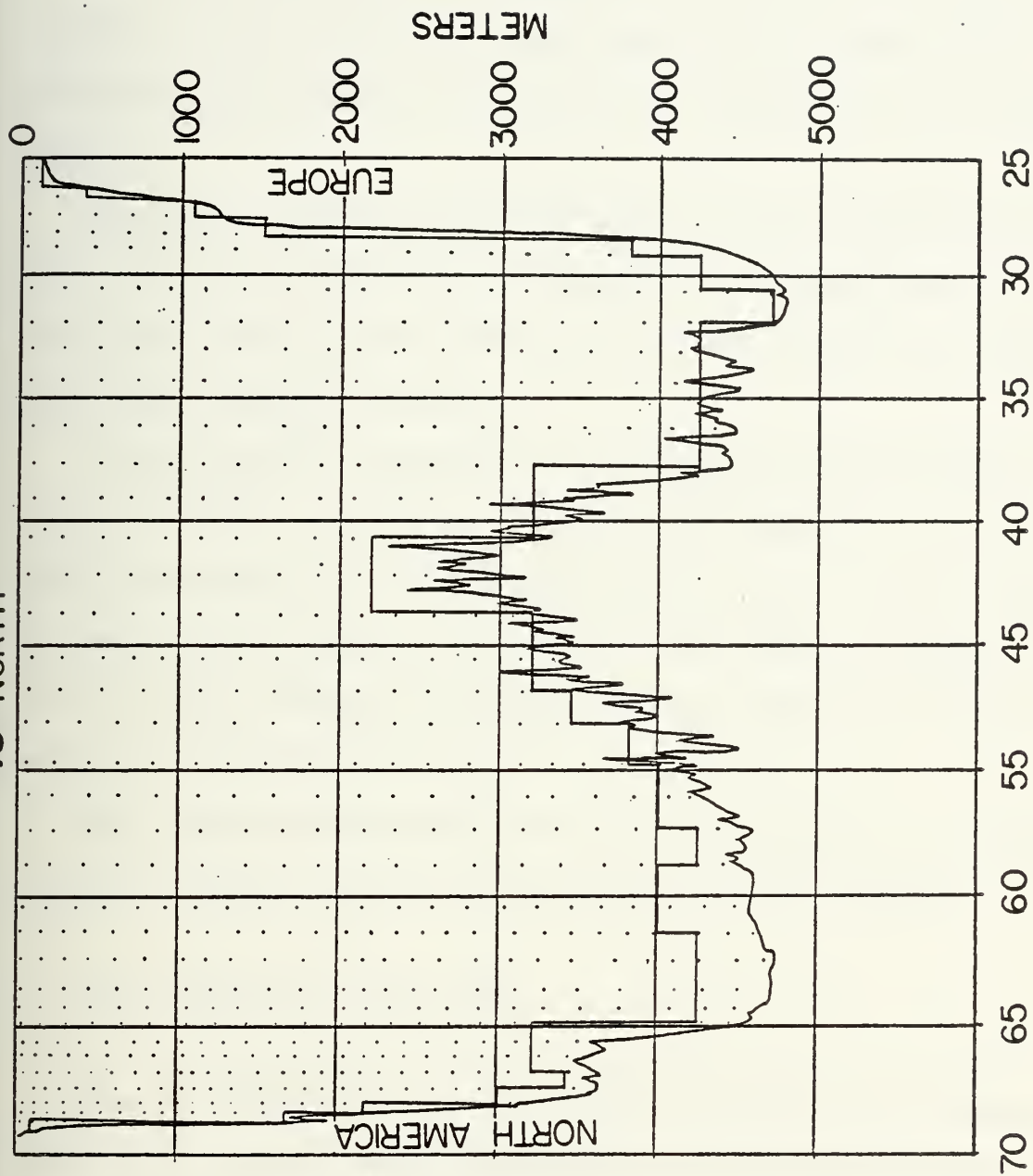


Figure 8

to give estimates of the net transport of these three quantities across the bottom area of the entire latitude section.

The values thus determined were added to those previously computed from the surface to the deepest common depth of each station pair to yield the total net transport of mass, salt, and heat for the latitude section.

Each time the level of no motion input is varied, the net transports vary. The level of no motion was considered established when the net flux of mass and salt across the entire latitude section was as close to zero as was considered feasible.

It was essentially impossible to attain exact zero net fluxes of both salt and mass simultaneously*, and it was necessary to establish which flux balance was to be the governing criterion. For this study zero mass flux was considered the primary requirement for balance, with zero salt flux a secondary requirement; however, both flux values were required to approach zero closely.

Once a satisfactory balance of mass and salt transport was achieved, the heat transport value for the latitude section was recorded.

C. IDENTIFICATION OF WATER MASSES

Prior to determining a general circulation pattern for the Upper, Intermediate, and Deep and Bottom Waters of the North Atlantic Ocean, it was necessary to identify the water masses in each of the seven latitude sections. The identification process consisted of matching known

*This appears to result from the data spacing, data interpolation and extrapolation techniques, and computer procedures.

temperature and salinity parameters for specific water masses to the interpolated values of temperature and salinity with depth provided for each pair of stations in each latitude section.

Defant (1961), Sverdrup et al. (1942), Williams et al. (1968), and Wright and Worthington (1970) were consulted with each providing specific temperature and salinity parameters for the water masses of the North Atlantic Ocean. However, no one author's criteria fit the data adequately. Therefore, the parameters finally utilized to identify the water masses were selected from the four authors, with the parameters for the transitional waters supplied by this author. Table 3 provides the listing of limits for the temperature and salinity criteria utilized in this study.

In addition to Table 3, some qualifying remarks must be made concerning the identification of the water masses. It will be noted that no parameters are given for surface waters. For this study, North Atlantic Surface Water is considered to be that layer of water exhibiting temperature and salinity variation overlying the central water mass. If no temperature or salinity variation was noted and North Atlantic Central Water parameters were present to the surface, surface water was depicted as extending to the bottom of the mixed layer as determined from temperature and salinity data. Also, in the cases where central water characteristics extended too deep to be reasonable, i.e. deeper than 1000 meters, a minimum salinity value was used as a lower limit. This method was chosen since the minimum salinity value is characteristic of intermediate waters.

Figures 9 through 15 depict the various water masses and transitional waters present. The dark horizontal line indicates the location of the level of no motion for each latitude section.

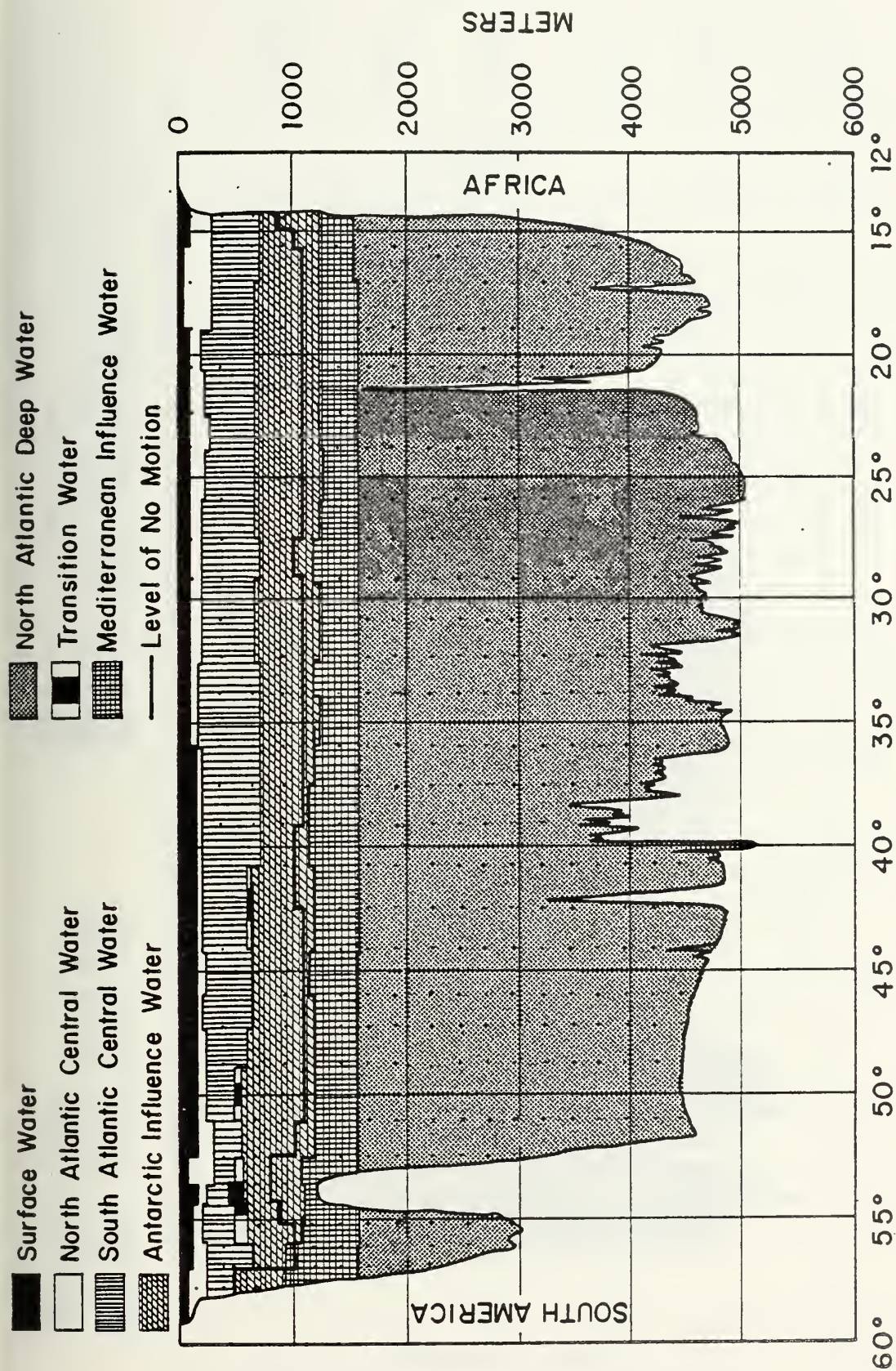
TABLE III

Temperature and Salinity Criteria for Water Mass
Identification in the North Atlantic Ocean

| I. | <u>Specific Water Masses</u> | <u>Temperature</u> | <u>Salinity</u> | <u>Author</u> |
|-----|--------------------------------------|-----------------------------------------|-----------------------------------|-------------------------|
| | Antarctic Bottom Water | -1.4°C | 34.66‰ | Defant |
| | North Atlantic Deep Water | 1.8° to 4.0°C | 34.89‰ - 35.00‰ | Wright & Worthington |
| | Antarctic Inter- mediate Water | 3° to 5°C | 34.1‰ - 34.6‰ | Defant |
| | Arctic Inter- mediate Water | 3.5°C | 34.88‰ | Sverdrup |
| | North Atlantic Intermediate Water | 3.2° to 6.5°C | 34.73‰ - 34.88‰ | Several |
| | Mediterranean Intermediate Water | 6° to 10°C | 35.3‰ - 36.4‰ | Defant |
| | North Atlantic Central Water | 8° to 18°C | 35.1‰ - 36.2‰ | Sverdrup |
| | South Atlantic Central Water | 6° to 18°C | 34.65‰ - 36.0‰ | Williams |
| II. | <u>Transitional Water Masses</u> | <u>Temperature</u> | <u>Salinity</u> | |
| | Mediterranean Influence Water | 3.8° to 5.84°C | 34.88‰ - 35.3‰ | |
| | Antarctic Influence Water | 4.5° to 6.56°C | 34.61‰ - 34.88‰ | |

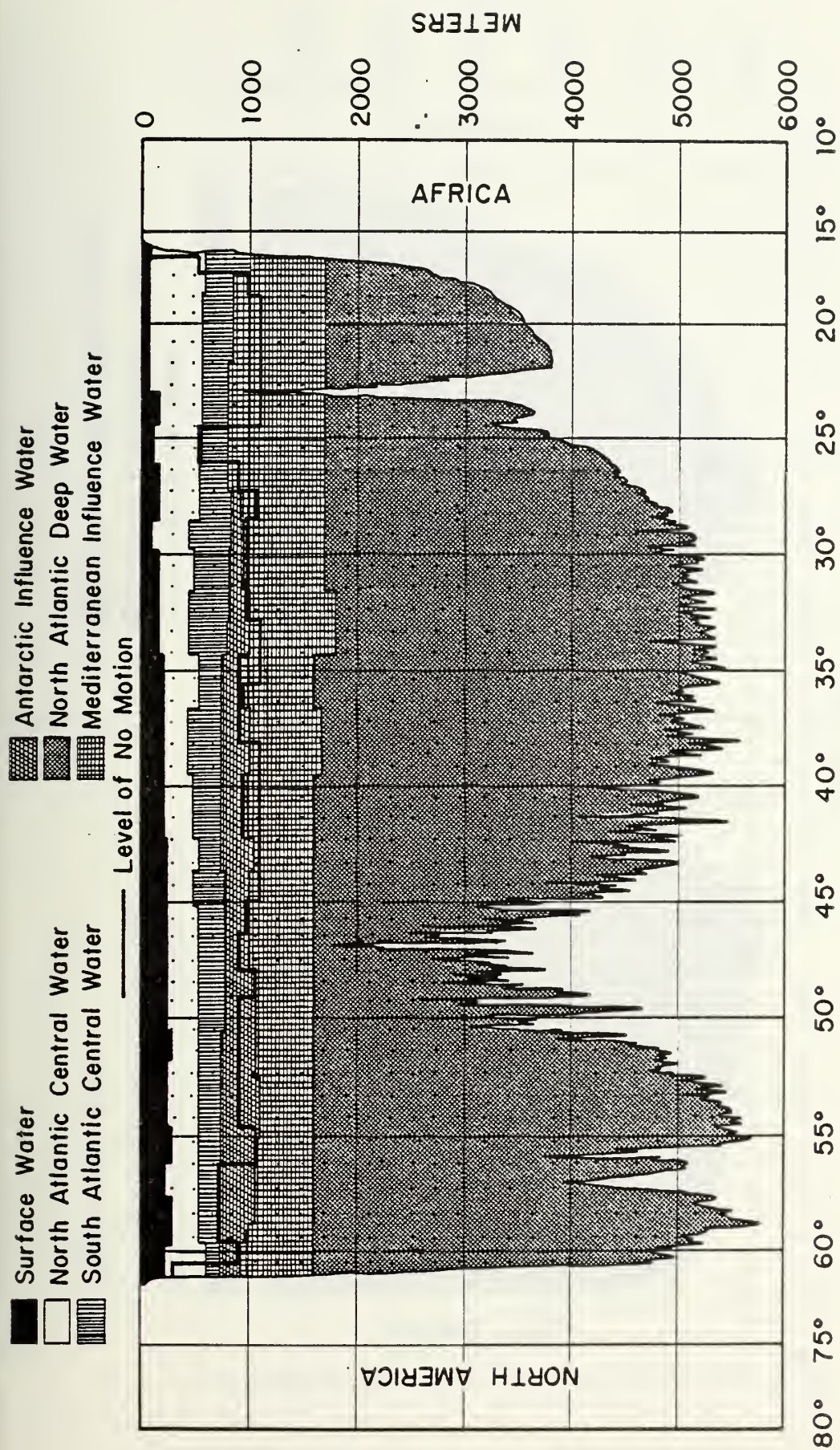
FIGURES 9-15

| | | | |
|---------------------------|------------------------------------|-------|----|
| FIGURE 9 - Water masses: | 8 ⁰ N latitude section | ----- | 46 |
| FIGURE 10 - Water masses: | 16 ⁰ N latitude section | ----- | 47 |
| FIGURE 11 - Water masses: | 24 ⁰ N latitude section | ----- | 48 |
| FIGURE 12 - Water masses: | 32 ⁰ N latitude section | ----- | 49 |
| FIGURE 13 - Water masses: | 36 ⁰ N latitude section | ----- | 50 |
| FIGURE 14 - Water masses: | 40 ⁰ N latitude section | ----- | 51 |
| FIGURE 15 - Water masses: | 48 ⁰ N latitude section | ----- | 52 |

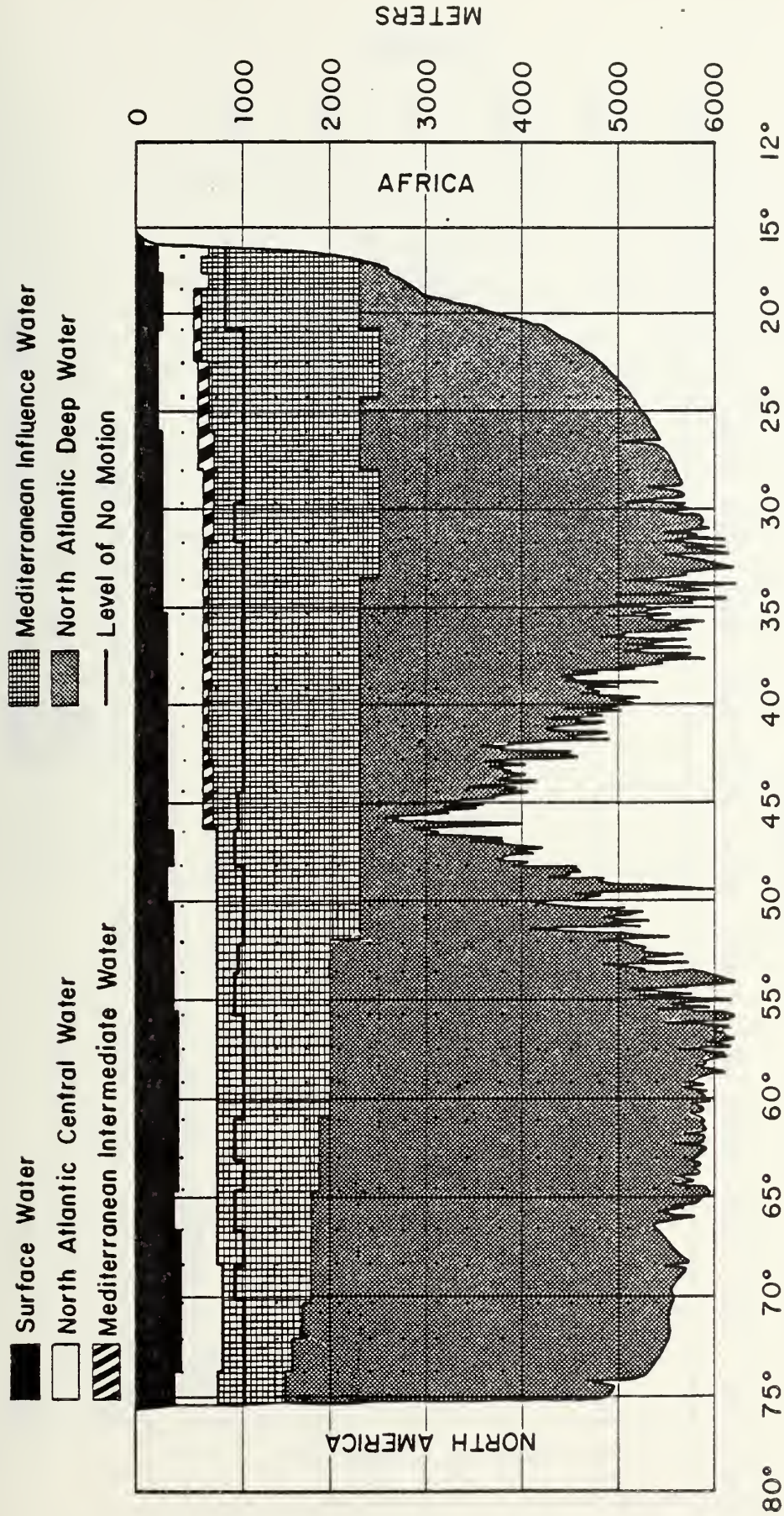


8° North

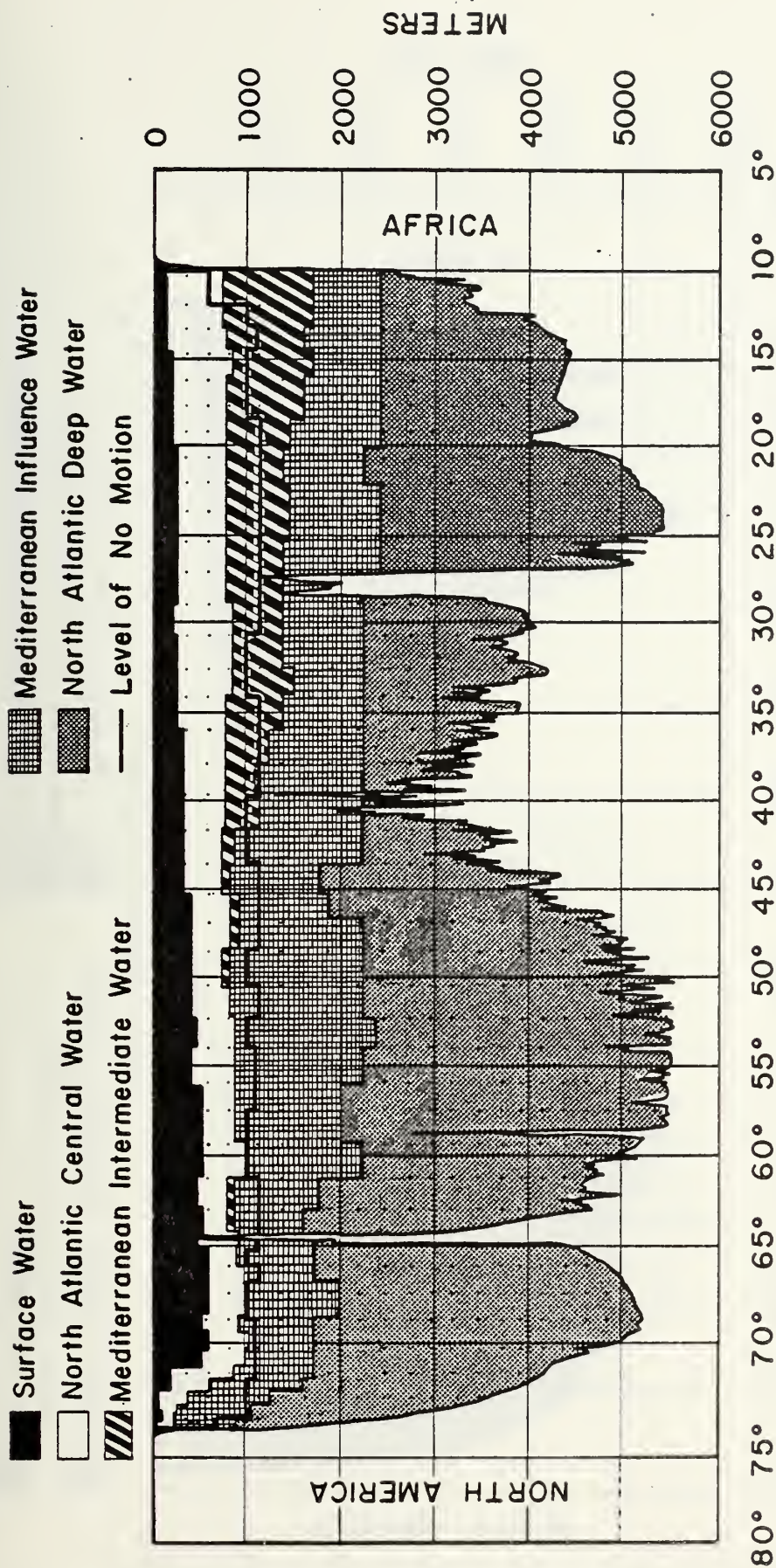
Figure 9



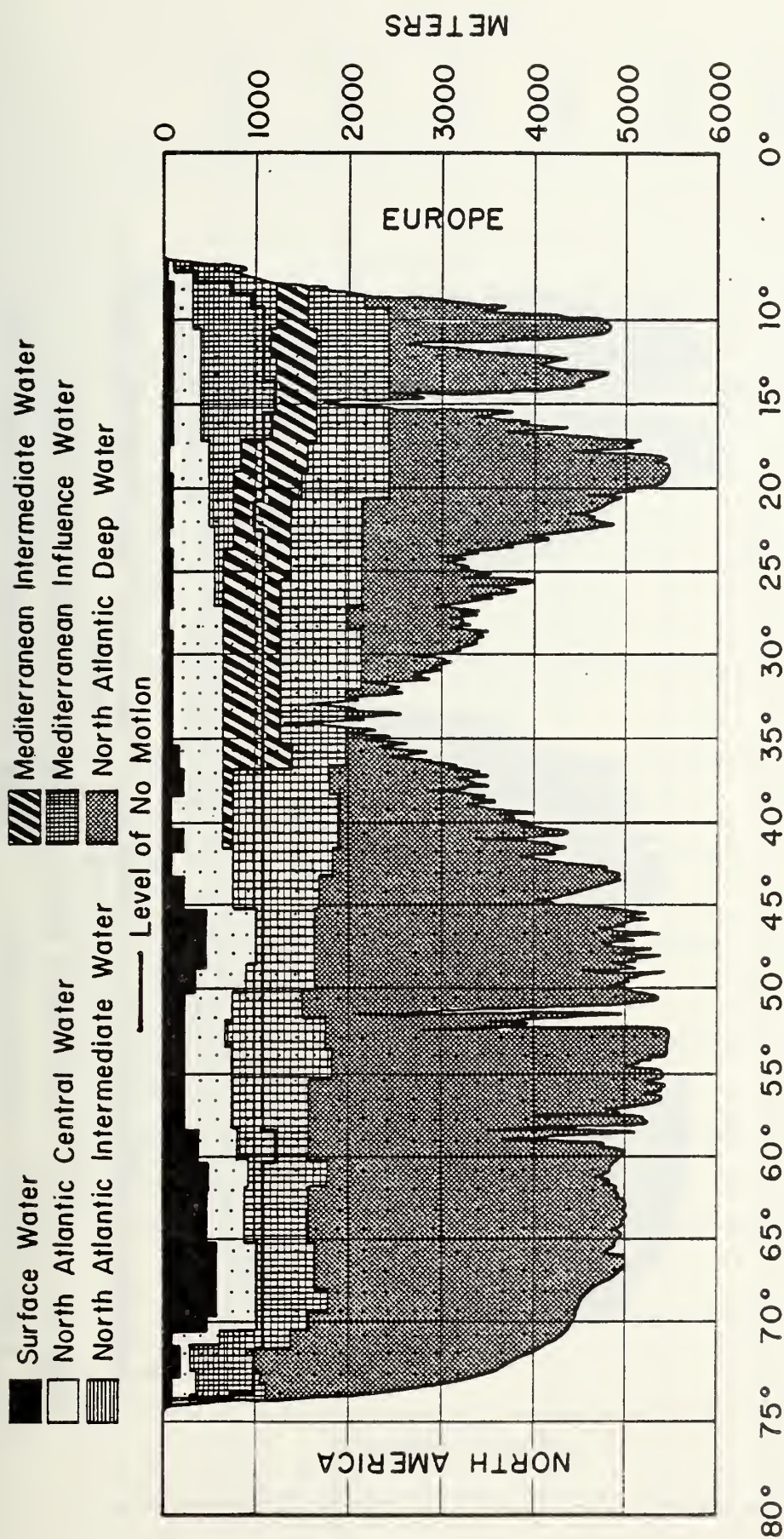
16° North
Figure 10



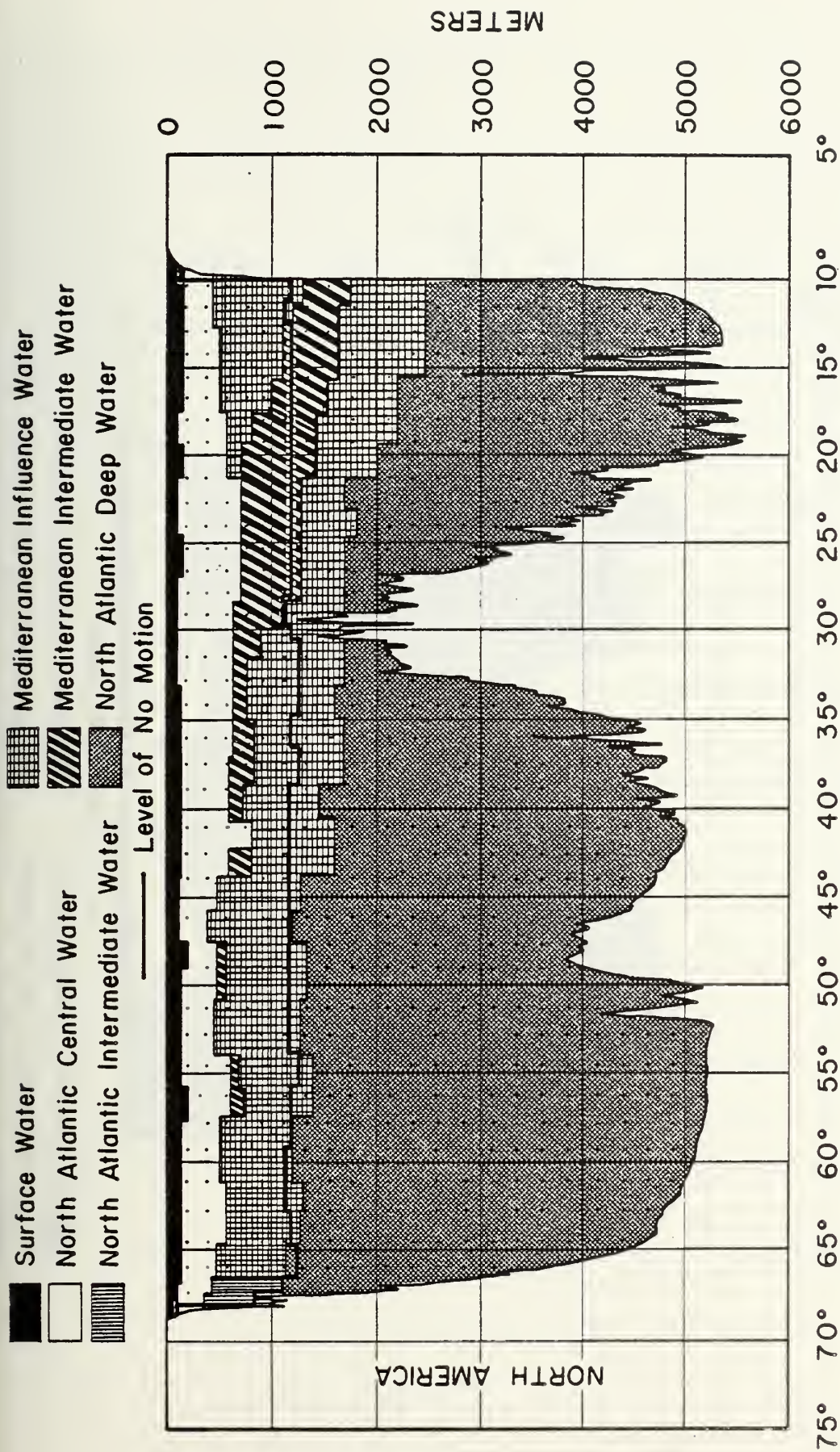
24° North
Figure 11



32° North
Figure 12

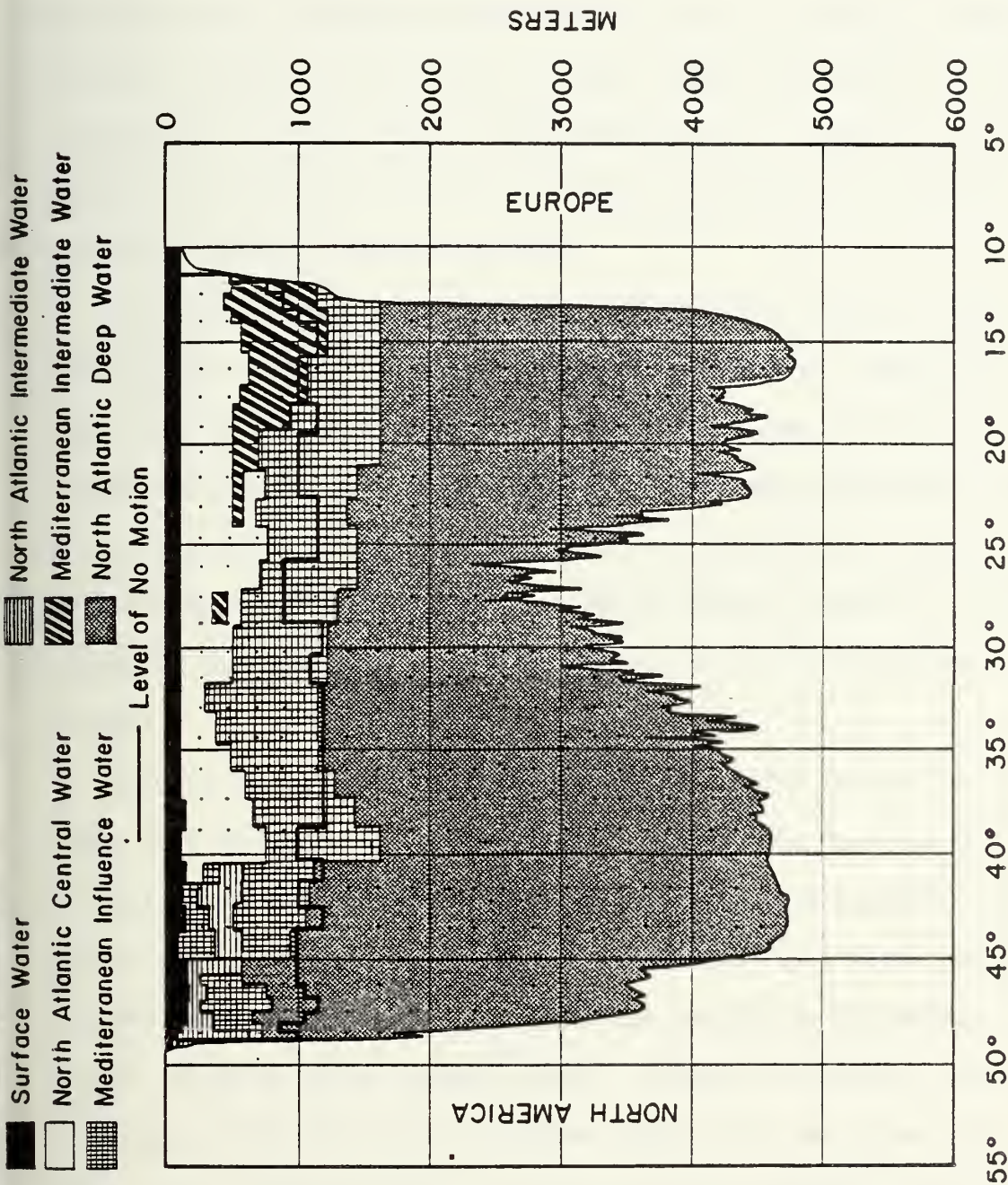


36° North
Figure 13



40° North

Figure 14



48° North
Figure 15

D. DETERMINATION OF THE GENERAL CIRCULATION PATTERN FOR UPPER, INTER-MEDIATE, AND DEEP AND BOTTOM WATER

After the individual water masses for all seven latitude sections had been identified, the water column between pairs of stations in each of the seven sections was divided into three layers: Upper Water, consisting of surface and central waters; Intermediate Water, composed of all intermediate and transitional waters; and Deep and Bottom Water, which consists entirely of North Atlantic Deep Water.

Next, the absolute mass transport for the three layers of water for each pair of stations was computed. This consisted of adding, for all station pairs, the mass transport values between sequential pairs of standard depths for each layer; this yielded an integrated vector quantity of mass transport for each layer (for this study positive values indicate northward transport, and negative values southward transport). Appendix A contains the tabulated results in detail for each of the seven latitude sections.

The mass transport vectors for all station pairs in each of the three layers then were plotted. These vectors were summed for each layer across the entire latitude section yielding a net layer mass transport value. The sum of the net layer mass transports for the three layers in each latitude section was required to match the previously determined mass balance figure to three decimal places. Figures 16 through 18 depict the computed integrated mass transport vectors for the three layers of water. The values depicted in these figures are rounded to the first or second decimal places; Appendix A shows the detailed values to greater accuracy.

The next task was the determination of the general circulation pattern for the Upper, Intermediate, and Deep and Bottom Waters based upon the net mass transport values across each of the latitude circles (see Figures 20 through 22).

To determine a reasonable circulation pattern along each of the latitude sections a pattern of cyclonic and anticyclonic eddies was constructed. The idea of using this extensive pattern of eddies may raise doubts in the minds of some oceanographers, but Robinson (1976) states "eddies are found almost everywhere they are looked for," and the report of the ARIES expedition pointed out "mid-ocean eddies extended from the sea surface to the bottom" (Robinson, 1976).

The pattern of circulation between the seven sections was then constructed. It will be noted that no eddies are shown in the intervening areas between the latitude sections, due to the fact that no direct synoptic measurements were available for these regions. However, it is the author's opinion that the hypothetical mass circulation depicted in these areas is the net result of mass distribution due to undefined meso-scale ocean eddies.

One additional point of clarification must be made. It will be noted that symbols for the loss and gain of water occur throughout the circulation diagrams. Although these symbols appear as specific point sources and sinks, that is not the author's intention. The symbols merely indicate amounts of water that must upwell or sink in these general areas in order to maintain continuity of mass between latitude sections and between the three layers of water.

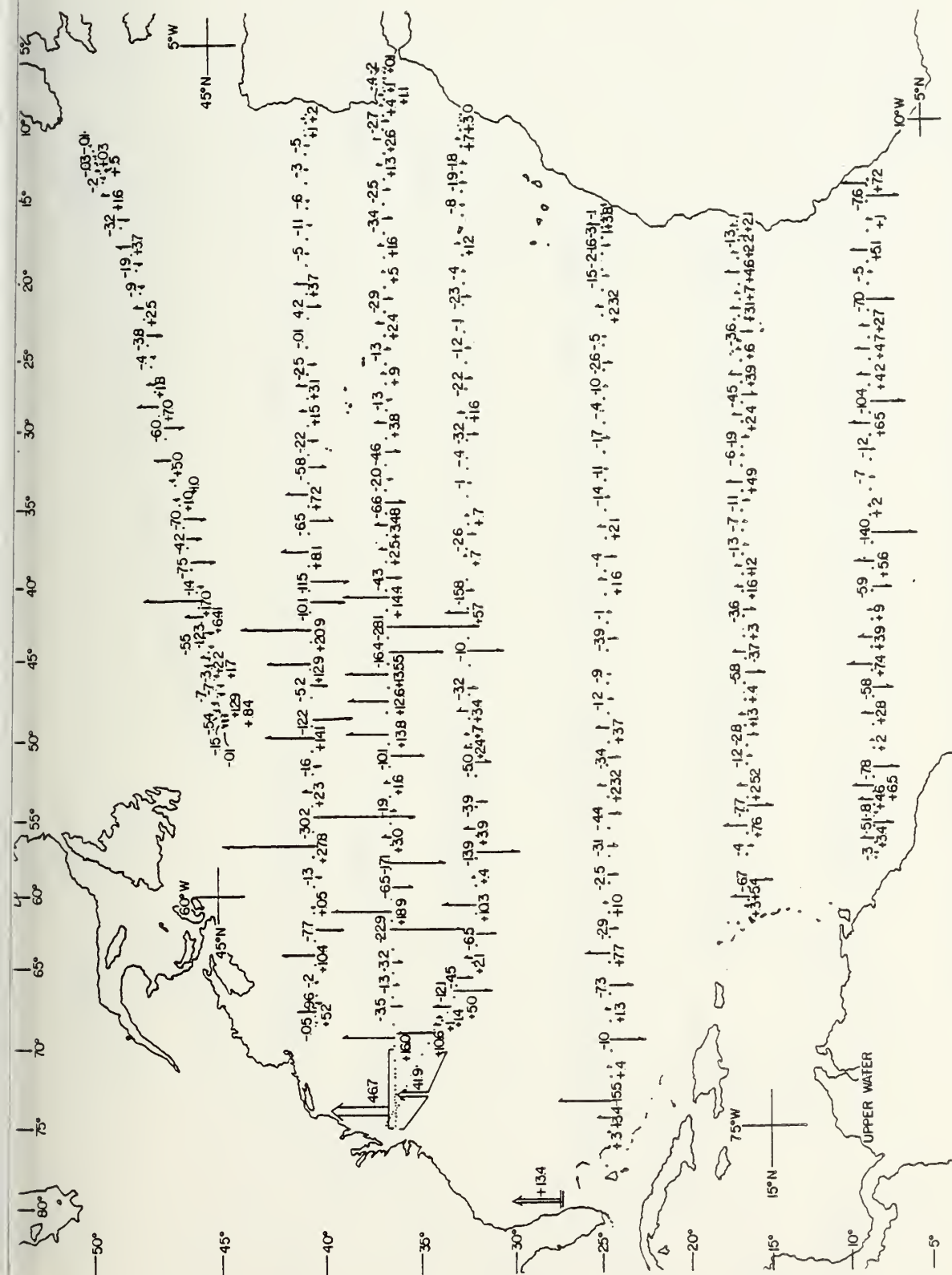


Figure 16. Integrated Mass Transport Vectors - Upper Water

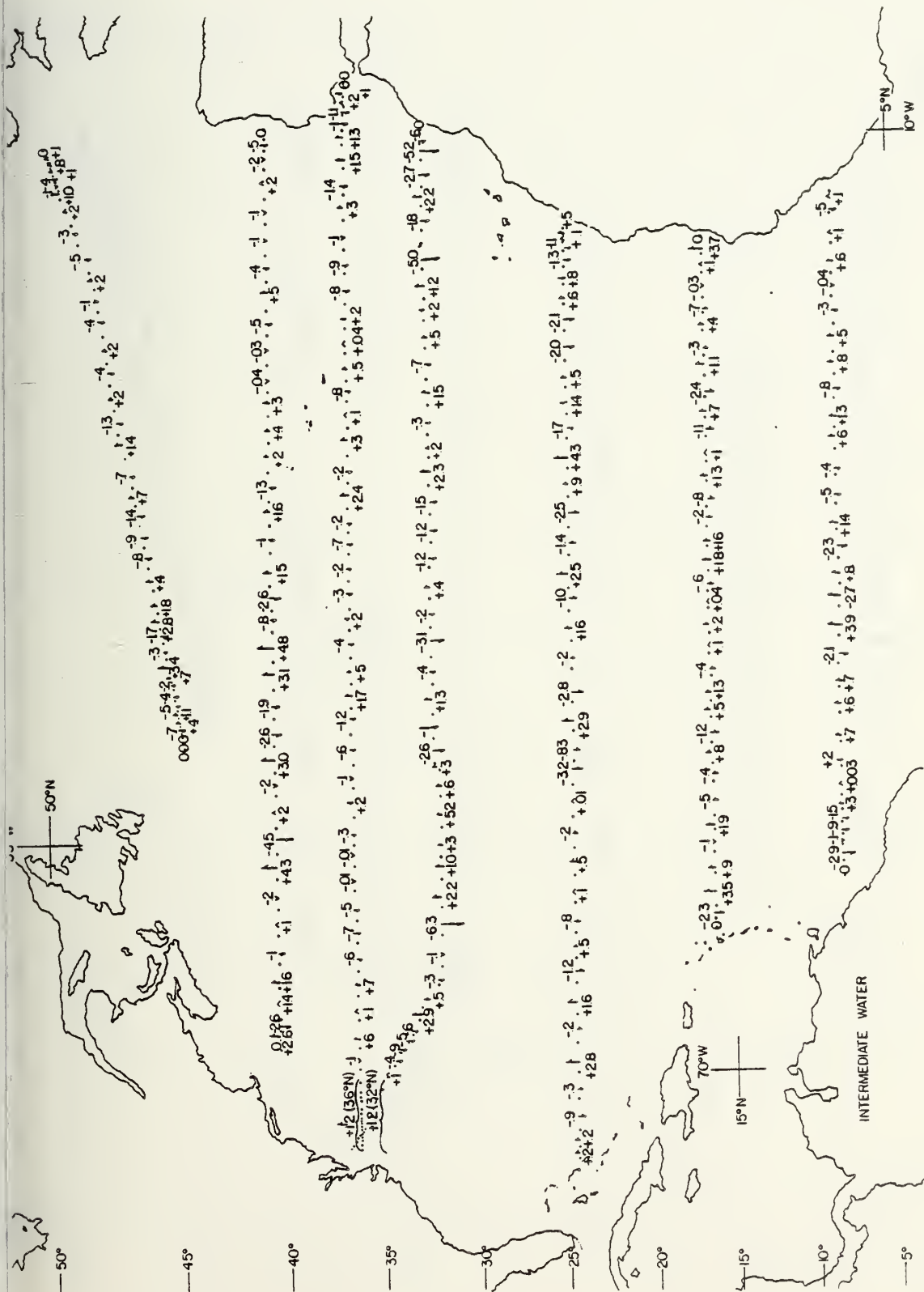


Figure 17. Integrated Mass Transport Vectors - Intermediate Water

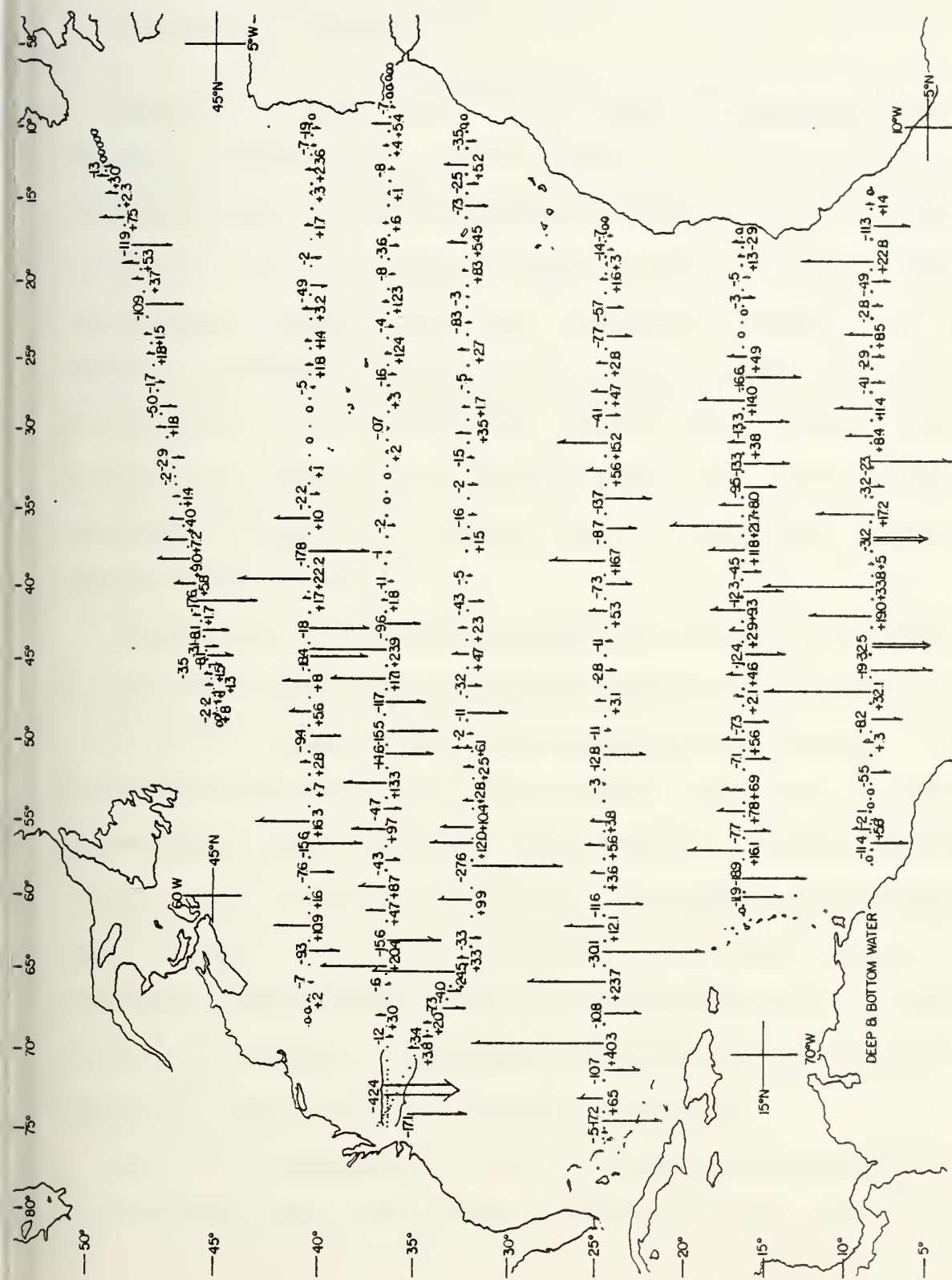


Figure 18. Integrated Mass Transport Vectors - Deep and Bottom Water

V. DISCUSSION OF RESULTS

A. THE LEVEL OF NO MOTION

The method utilized to determine the level of no motion was that proposed by Sverdrup et al. (1942). According to this method, the horizontal reference surface chosen for the ensemble of station pairs in a latitude section is considered to form the level of no motion when the net transport of mass and salt above the reference surface is equal and opposite in direction to that below the reference surface across the entire latitude section. The depths of the reference surfaces comprising the level of no motion for all latitude sections are listed in Table IV, and the distribution of the reference levels has been shown for each section in Figures 9-15.

A comparison of the level of no motion for each of the latitude sections used in this study with those of previous works, notably those of Riley (1951), Neumann (1954), and Jung (1955), was also made. Reasonable correlation was found with Jung's results, which were also based on the procedure of Sverdrup et al. (1942), and with a portion of Neumann's results, based on Defant's (1941) method. The agreement with Neumann's results exists with only his 20°N and 30°N sections and failed at both low and high latitudes where his "zero level" either shoals or deepens in response to changes in the planetary vorticity with latitude. The comparison of these results is contained in Table V.

Jung (1955) stated that his level of no motion coincided with the 7° isothermal surface, which was also Sverdrup's assumed level for the

TABLE IV

Breakdown of the Level of No Motion for all Latitude Sections

I. 8° North Section (30 Pairs of Stations)

| <u>LONM</u> | <u>No. of Times Used/Section</u> | <u>% of Total</u> |
|-------------|----------------------------------|-------------------|
| 1100 meters | 18 | 60% |
| 1000 meters | 7 | 23.3% |
| 900 meters | 2 | 6.7% |
| 800 meters | 2 | 6.7% |
| 500 meters | 1 | 3.3% |
| | <u>30</u> | <u>100.0%</u> |

II. 16° North Section (33 Pairs of Stations)

| <u>LONM</u> | <u>No. of Times Used/Section</u> | <u>% of Total</u> |
|-------------|----------------------------------|-------------------|
| 1100 meters | 13 | 39.4% |
| 1000 meters | 5 | 15.1% |
| 900 meters | 10 | 30.3% |
| 750 meters | 2 | 6.1% |
| 500 meters | 2 | 6.1% |
| 50 meters | 1 | 3.0% |
| | <u>33</u> | <u>100.0%</u> |

III. 24° North Section (37 Pairs of Stations)

| <u>LONM</u> | <u>No. of Times Used/Section</u> | <u>% of Total</u> |
|-------------|----------------------------------|-------------------|
| 1100 meters | 25 | 67.6% |
| 1050 meters | 1 | 2.7% |
| 1000 meters | 5 | 13.5% |
| 900 meters | 5 | 13.5% |
| 50 meters | 1 | 2.7% |
| | <u>37</u> | <u>100.0%</u> |

IV. 32° North Section (53 Pairs of Stations)

| <u>LONM</u> | <u>No. of Times Used/Section</u> | <u>% of Total</u> |
|-------------|----------------------------------|-------------------|
| 1100 meters | 29 | 54.7% |
| 1000 meters | 18 | 33.9% |
| 900 meters | 1 | 1.9% |
| 700 meters | 1 | 1.9% |
| 500 meters | 2 | 3.8% |
| 100 meters | 1 | 1.9% |
| 50 meters | 1 | 1.9% |
| | <u>53</u> | <u>100.0%</u> |

TABLE IV (Cont'd)

V. 36° North Section (59 Pairs of Stations)

| <u>LONM</u> | <u>No. of Times Used/Section</u> | <u>% of Total</u> |
|-------------|----------------------------------|-------------------|
| 1250 meters | 1 | 1.7% |
| 1200 meters | 3 | 5.1% |
| 1150 meters | 1 | 1.7% |
| 1100 meters | 39 | 66.1% |
| 1000 meters | 8 | 13.6% |
| 700 meters | 2 | 3.4% |
| 500 meters | 1 | 1.7% |
| 400 meters | 1 | 1.7% |
| 150 meters | 1 | 1.7% |
| 100 meters | 1 | 1.7% |
| 50 meters | 1 | 1.7% |
| | <u>59</u> | <u>100.0%</u> |

VI. 40° North Section (37 Pairs of Stations)

| <u>LONM</u> | <u>No. of Times Used/Section</u> | <u>% of Total</u> |
|-------------|----------------------------------|-------------------|
| 1300 meters | 2 | 5.4% |
| 1250 meters | 9 | 24.3% |
| 1200 meters | 18 | 48.6% |
| 1150 meters | 4 | 10.8% |
| 1100 meters | 1 | 2.7% |
| 850 meters | 1 | 2.7% |
| 150 meters | 1 | 2.7% |
| 50 meters | 1 | 2.7% |
| | <u>37</u> | <u>100.0%</u> |

VII. 48° North Section (39 Pairs of Stations)

| <u>LONM</u> | <u>No. of Times Used/Section</u> | <u>% of Total</u> |
|-------------|----------------------------------|-------------------|
| 1200 meters | 12 | 30.8% |
| 1100 meters | 2 | 5.1% |
| 1000 meters | 14 | 35.9% |
| 900 meters | 4 | 10.3% |
| 800 meters | 1 | 2.6% |
| 500 meters | 1 | 2.6% |
| 300 meters | 1 | 2.6% |
| 150 meters | 1 | 2.6% |
| 100 meters | 2 | 5.1% |
| 50 meters | 1 | 2.6% |
| | <u>39</u> | <u>100.0%</u> |

TABLE V

A COMPARISON OF THE LEVEL OF NO MOTION FOR THE NORTH ATLANTIC OCEAN

| LAT. | BAKER* | LAT. | JUNG (1955)+ | LAT. | NEUMANN (1954)+ | LAT. | RILEY (1951)+ |
|------|-----------|------|----------------------------------------------------|------|-----------------|------|---------------------------------------------|
| 8° | 900-1100m | 0° | 900m | | | 0° | 900m |
| 16° | 750-1100m | 9° | 55 -30 W long 25 20 15 100m 75m 50m 40m | 10° | 500m | 9° | 34.95 isohaline and 2000-2500; 3000-3500 |
| 24° | 900-1100m | 18° | 85 -80 1000m 60 -20 900m | 20° | 880m | 18° | " |
| 32° | 700-1100m | 27° | 75 -45 1000m 40 -15 900m | 30° | 1200m | 27° | " |
| 36° | 750-1250m | 36° | 70 -40 1000m 35 30 -20 15 -10 900m 800m 700m | | | 36° | 3000m |
| 40° | 850-1300m | 45° | 45 -25 1000m 20 -5 800m | | | 45° | " |
| 48° | 800-1200m | 54° | 50 -35 1000m 30 -15 800m | 50° | 1900m | 54° | 2500m |
| | | 63° | 60 -55 40 -0 ; 0 -5 E 700m 500m | | | | |

* Baker's results excluding shallow-water, near-shore station values

+ Results as read from Jung (1955), Table II

southeastern North Atlantic Ocean. On comparing the levels of no motion used in this study with the isothermal and isohaline diagrams contained in the Atlantic Ocean Atlas (Fuglister, 1960), no correlation was found to exist with any isohaline surface; only the 24°N section level of no motion exhibited any correlation with an isothermal surface, coinciding with the 6°C isothermal surface for a sizable portion of the latitude section.

Finally, an examination of the variability in depth of the level of no motion over the area of interest in this study was made and is shown in Table IV. The level was found to remain rather consistent in depth with 85% of all station pairs found to have their segment of the level of no motion residing between 900 meters and 1200 meters. If all near-shore shallow water stations are ignored, leaving only the deepwater stations, 93% of the level of no motion segments lie between 900 meters and 1200 meters.

B. MASS AND SALT TRANSPORT

Prior to determining a value for the heat transport across each of the latitude sections, the best possible balance of water mass and salt was required. The requirement of zero net transport of mass was considered the primary criterion for continuity with the salt balance a secondary criterion. This procedure was adopted after it was found impossible in several sections to arrive at a condition where both a zero net flux of mass and salt existed and the level of no motion remained consistent in depth over the entire latitude section. However, with the adopted procedure, it was possible to obtain excellent mass balance results and satisfactory salt balance results for all latitude sections.

Table VI summarizes the computed net mass and salt transport values for the seven latitude sections of interest; this is an indication of the degree to which the intended mass and salt continuity was attained.

It is interesting to note in Jung's (1955) paper using Meteor Atlas data that he also was unable to achieve a zero net flux of salt across his latitude sections. On comparing his results with those obtained in this work, a remarkable similarity is found. His largest net flux of salt occurs at 45°N whereas in this study it occurs at 40°N , while in both works the most satisfactory salt balance occurs at 36°N latitude. Table VII contains the net salt transports from Jung's (1955) paper.

C. HEAT TRANSPORT

The net meridional transport of heat across a latitude section of the ocean can be represented by the expression

$$C_{ps} (T_n - T_s) \rho_s V_{ns} ;$$

or, if we assume the specific heat at constant pressure of seawater, C_{ps} , to be unity, by

$$(T_n - T_s) \rho_s V_{ns} , \tag{8}$$

where $\rho_s V_{ns}$ is the meridional mass transport, and the north-south water temperatures are designated T_n and T_s . For a mass balance to exist across a latitude section, as is required by mass continuity, the mass transports $\rho_s V_{ns}$ (north) and $\rho_s V_{ns}$ (south) must cancel. However, the heat transport value does not necessarily vanish since the temperatures of the waters transported in opposing directions may differ resulting in a net meridional flux of heat.

TABLE VI

NET MASS AND SALT TRANSPORT VALUES

| Latitude | 48°N | 40°N | 36°N | 32°N | 24°N | 16°N | 8°N |
|------------------------------------|---------|---------|---------|--------|---------|----------|----------|
| Net Mass* Transport | .00491 | -.01933 | -.31651 | .04297 | -.02362 | .13161 | .06502 |
| Net Salt ⁺ Transport | 3.12456 | 9.45634 | -.00718 | .15148 | .10100 | -6.23340 | -5.23500 |

* All mass units $\times 10^{12}$ gm/sec

+ All salt units $\times 10^{12}$ o/oo/sec

TABLE VII

NET SALT TRANSPORT FOR THE NORTH ATLANTIC OCEAN
FROM JUNG (1955) TABLE V

| Latitude | 63° | 54° | 45° | 36° | 27° | 18° | 9° |
|------------------------|-------|-------|--------|-------|-------|-------|-------|
| Net Salt* Transport | 1.096 | 5.992 | 36.559 | -.003 | 8.095 | 6.019 | 1.812 |

* All salt units $\times 10^{12}$ ($^{\circ}/\text{oo} - 30$)/sec

This method of computation is not the only procedure available for measuring meridional heat transport in the ocean. Other methods have been proposed such as those of Sverdrup (1955) and Vander Haar and Oort (1973). However, since this method is based on computations from direct measurements of salinity and temperature it was selected as the most suitable approach.

Table VIII contains the net heat transport values determined by this work. Figure 19 gives a comparison of these values with those obtained by Jung (1955); Sverdrup (1956); Sellers (1965); Vander Haar and Oort (1973); and a study conducted by Jung in 1974 through 1976 using this study's data, but neglecting the peripheral areas.

D. OCEANIC EDDY CIRCULATION

The pattern of cyclonic and anticyclonic eddies used in the general circulation pattern of the present investigation was a natural outgrowth of the pattern of mass transport vectors computed for the North Atlantic Ocean. Figures 16 through 18, which depict the integrated mass transport vectors for the three layers of water, show a remarkably consistent pattern of opposing flow for adjacent pairs or larger combinations of oceanographic stations. To accommodate the net transport of mass across each latitude section, an eddy circulation pattern was drawn.

This concept of eddy circulation existing in the North Atlantic Ocean is consistent with past observations. Historically, observations of eddy circulation as found in the Gulf Stream rings has been reported by Iselin (1936 , 1940), Fuglister (1947), Iselin and Fuglister (1948), Fuglister and Worthington (1951), Fuglister (1963), Barrett (1963), Fuglister (1971), Richardson (1976) and Parker (1971). The results of

TABLE VIII

NET HEAT TRANSPORT VALUES

| Latitude | 48°N | 40°N | 36°N | 32°N | 24°N | 16°N | 8°N |
|------------------------|----------|-----------|-----------|-----------|----------|---------|-----------|
| Net Heat* Transport | 95.20546 | 135.06939 | 140.84598 | 122.60636 | 76.69357 | 9.29520 | -81.47400 |

* All heat values $\times 10^{12}$ cal/sec

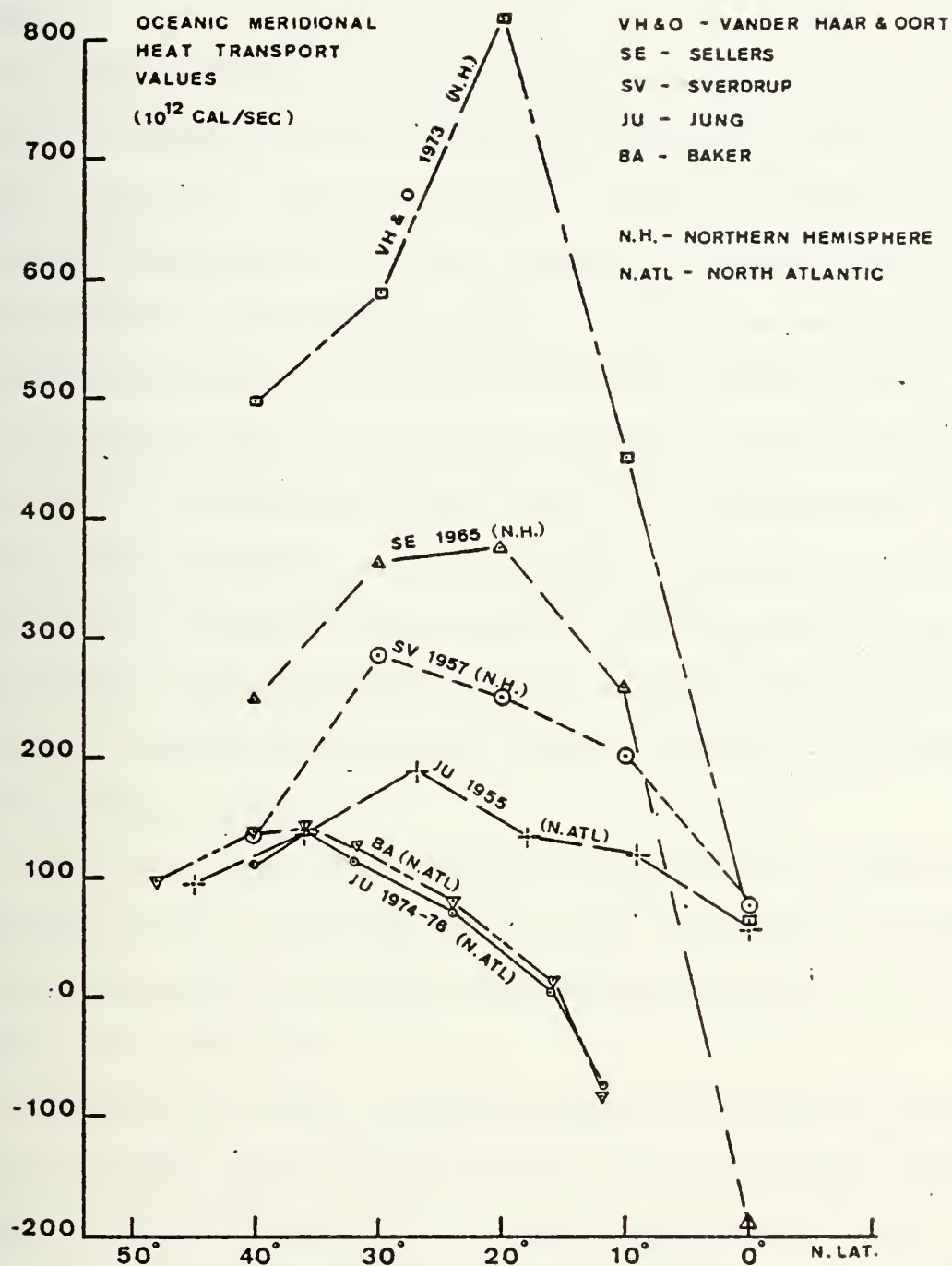


Figure 19. Comparison of Heat Transport Values for the North Atlantic Ocean and the Northern Hemisphere

these studies and of others began the investigation to identify this eddy phenomenon and to see its association with the general circulation of the oceans.

The eddy phenomenon, technically named low frequency mesoscale variability, is composed of slow fluctuations on the order of 100 to 200 kilometers in diameter. These fluctuations or areas of variability usually take one of three recognized forms: meanders in the Gulf Stream, cyclonic and anticyclonic rings formed by meanders that have become separated from the Gulf Stream proper, and the mid-ocean eddies (Robinson, 1976).

The mid-ocean eddy, as an entity in itself, was first introduced in the results of the ARIES Expedition (1959-1960). The expedition's observations indicated that not only did mid-ocean eddies exist, but they are several orders of magnitude more energetic than the average circulation. Their results also indicated that the eddy structure extends from the surface to the ocean floor and has a typical radius of 100 to 200 kilometers (Robinson, 1976).

Today the existence of the eddy field and its general characteristics definitely has been established by the results of the Mode-1 experiment which produced the first synoptic map of mid-ocean eddies for a sizable portion of the deep ocean.

In examining the eddy circulation proposed along each latitude section for these layers of water, it will be noted that some eddies exhibit cyclonic circulation at the surface, becoming anticyclonic at depth. The opposite case also holds true. This reverse in circulation with depth has been observed by McCartney, Worthington, and Schmitz (1978). In their study of large cyclonic Gulf Stream rings in the Northern Sargasso Sea, moored current meter data indicated a strong cyclonic circulation

($45 \times 10^6 \text{ m}^3/\text{s}$) overlying a much weaker anticyclonic circulation ($4 \times 10^6 \text{ m}^3/\text{s}$), with the reversal occurring at approximately 200m.

These results were then assumed to hold true for the case of anticyclonic circulation overlying cyclonic circulation.

Lastly, although many questions remain to be answered concerning the source(s) of mid-ocean eddies and how they are related to the general circulation of the North Atlantic Ocean, given their strength, long life, and ubiquitous nature, it can be assumed that they contribute significantly to the transfer of mass, salt, and heat in the North Atlantic Ocean.

E. THE GENERAL CIRCULATION PATTERN AND ITS COMPARISON WITH PREVIOUS WORKS

The following discussion of the general circulation of the Upper, Intermediate, and Deep and Bottom Waters as determined in this study has placed special emphasis on the comparison of these results with those of Sverdrup et al. (1942), Jung (1955), and Worthington (1976). However, other authors were referenced for more limited comparisons. The work of Defant (1941) was found extremely useful for his descriptive coverage of the current system of the North Atlantic, yet comparisons were limited to those authors whose descriptions included actual volume transport figures.

In making this comparison with Worthington's work, some difficulty was encountered. Worthington has divided the North Atlantic into five layers based on temperature criteria. Table IX lists these five layers of North Atlantic Water.

In relating these two works it was found that Worthington's Warm Water, Upper and Mid-Thermocline layers correspond to this study's Upper Water in the absence of Mediterranean Intermediate Water. In the presence

TABLE IX
THE FIVE LAYERS OF NORTH ATLANTIC WATER*

| <u>Layer</u> | <u>Temperature Range</u> |
|----------------------|--------------------------|
| 1. Warm Water | Warmer than 17°C |
| 2. Upper Thermocline | 12°C - 17°C |
| 3. Mid-Thermocline | 7°C - 12°C |
| 4. Lower Thermocline | 4°C - 7°C |
| 5. Deep | Colder than 4°C |

* According to Worthington, 1976.

of Mediterranean Intermediate Water the correlation ends at the Mid-Thermocline layer's 10°C isotherm. The Intermediate Water of this study in turn corresponds to the Lower Thermocline layer, or the Lower Thermocline plus that portion of the Mid-Thermocline layer colder than 10°C , depending upon the absence or presence of Mediterranean Intermediate Water. In all cases, the Deep and Bottom Water corresponds to Worthington's Deep layer.

In making the comparison of transport values, it was noted that although Jung's paper considered mass transport, those of Sverdrup and Worthington utilized volume transport in terms of Sverdrups ($10^6 \text{ m}^3/\text{sec}$). To determine the significance of the error involved in such a comparison, the results of a study conducted by Cummings (1977) were used. Cummings compared a large sampling of mass transport values expressed in units of 10^{12} gm/sec and volume transport values in Sverdrups for the North Atlantic. His results indicated the values were consistent to within 2.7%. This error is considered well within acceptable limits.

1. The Circulation Pattern of the Upper Water*

The North Equatorial Current as depicted in Figure 20 is a broad east to west flowing current extending from 16°N to 24°N latitude. The primary flow is zonal in nature resulting from the influence of the Northern Hemisphere trade winds. The net transport across the 16°N and 24°N latitude sections results in a net convergence of 19.5 mass units in this region. Mass continuity is maintained by an outflow of 13.4 units into the Caribbean and a loss of 6.1 units by sinking from the upper levels to the Deep and Bottom Water off the coast of Africa.

*All mass units are in terms of 10^{12} gm/sec .

The value of the flow into the Caribbean is quite low when compared to the 30sv and 26sv as determined by Worthington and Sverdrup. The 6.1 units lost by sinking finds some support from Worthington's study which indicates 5sv sink from the warm water in this area. However, the sinking is limited in depth to the Upper Thermocline layer.

The outflow from the Caribbean through the straits of Florida again is the extremely low value of 13.4 units, less than 50% of Worthington's 30sv, Jung's 27.5 units, and slightly greater than half of Sverdrup's 26sv. No obvious reason for this anomalously low value is evident. Yet, this is the maximum transport possible as determined by the 27°N latitude section which spans the Florida Current. Some support for this value was found in Wertheim's (1954) study of flow rates and transport in the straits of Florida which indicated a transport of 14sv in December 1952, and 16-18sv in November and December 1953 (Cummings, 1977). The data for the 16° and 24° sections also are autumn data (October-November, 1957) as were the Wertheim data; the 27° data were, however, early summer data from June 1955.

At approximately 30°N the Florida Current is joined by the Antilles Current flowing along the north and east sides of the West Indies. The transport associated with the Antilles current is 19.2 units resulting in a total net northward transport of 32.6 units for this portion of the Gulf Stream. The transport value of 19.2 units associated with the Antilles Current is much higher than the value of 5sv indicated by Worthington, and compensates the Gulf Stream somewhat for the small transport of the Florida Current. Support for this high transport value is found with Sverdrup who indicates that although the Antilles Current usually is considered to be nearer 12sv, it may reach a maximum of 15 to 20sv.

North of the junction of the Antilles Current and the Florida Current, we see the Gulf Stream supplemented by 6.3 units upwelled from the Intermediate Water and 7.8 units from the Sargasso Sea. These additions are supported by Sverdrup et al. (1942) p. 676, who note that the downstream intensification, after combining the Antilles Current and the Florida Current, is due to the addition of Sargasso Sea water and upwelled deep water.

We now have the maximum net northward transport of 46.7 units for the Gulf Stream found at 36°N latitude. This value is 61% of Worthington's value of 76.9sv as determined for 38°N latitude, but is much more comparable to Sverdrup's 55sv, and to Jung's 57.8 units determined for 36°N .

North of 36°N the flow again becomes zonal in nature. As the current proceeds easterly, it divides into two flows, one turning south to create the large return gyre of the North Atlantic Current. The return flow carries with it the majority of the transport, 32 units, leaving 15 units for the formation of the North Atlantic Current. Once again these values are low compared to Worthington, Sverdrup, and Jung, but the relative magnitudes of the currents are correct.

The North Atlantic Current then undergoes a division sending 4.2 units to join the Azores Current which travels southeasterly to join the Portugal Current. The northern element of the current flows northeasterly and is joined off the coast of England by 1 unit flowing north along the western coast of Europe.

The union of the Portugal Current and the Azores Current occurs northwest of the Straits of Gibraltar. The combined flow of 2.6 units proceeds southeasterly forming the Canary Current. Near 32°N this flow is augmented by 0.7 units upwelled from the Intermediate Water. The current then flows southwesterly along the west coast of Africa; as it

approaches 24°N the effects of the trade winds become evident with the eventual combining of the Canary Current with the North Equatorial Current.

At the Straits of Gibraltar, an exchange of 1.0 units with the Mediterranean occurs. This outflow of highly saline Mediterranean Water flows northwesterly towards Cape St. Vincent where it entrains 0.5 units of North Atlantic water and sinks to the Intermediate Water. This value for the exchange with the Mediterranean is low compared to the 2sv proposed by Sverdrup; however, it equals Worthington's 1sv.

After the division of the Gulf Stream, the southern component which forms the North Atlantic Gyre is found to divide again, forming two components: a more intense southward flow of 19.3 units extending east to 45°W longitude, and a very broad diffuse southward flow of 10.3 units extending from 41°W to 21°W . The transport value of the more westward portion of the gyre, acting as the principal mechanism of return flow for the Gulf Stream system, is found to be very similar to the 15-20sv proposed by Sverdrup, and the 19.4 units of Jung; but again it is found to be extremely low compared to the 60sv flow of Worthington's gyre.

It will be noted that within the gyre, several areas of upwelling occur. These locations and the quantities of water indicated, although not directly supported by the other studies, are required to maintain mass continuity between the latitude sections and the different layers involved.

In the region between 8°N and 16°N we find the Equatorial Counter-current flowing to the southeast, transporting 4.6 units. The current is found to extend from approximately 16°N , 57°W to 8°N , 25°W . These values are very comparable to limits established by Defant (1941), Table 147, in their longitudinal extent, but are found to extend far

beyond the 10°N northern latitude limit. This situation possibly could result from an anomalous migration of the Northern Hemisphere trade winds belt during 1957, thereby allowing the Equatorial Countercurrent to extend farther north than expected. Another explanation arises from the fact that the oceanographic stations of the 8°N section were occupied during May 1957, while those of the 16°N section were occupied in November 1957, each occurring during different phases of the annual north-south migration of the trade wind belt.

The influx of water from the South Equatorial Current amounts to 5.3 units. This value compares most favorably with all authors; however, the location of this addition is much further to the east than previously reported.

One last feature of this circulation pattern is the jet of northward flowing water forming an eastern boundary current off the coast of Africa and Europe. This flow begins at 8°N as a narrow high transport jet of 7.2 units, that continues northward with decreasing magnitude, throughout the entire area of interest. This feature has not been reported before in the general circulation of the upper waters of the Atlantic, although Lacombe and Tchernia (1960), Lacombe (1961), and Madelain (1967) have demonstrated that a current consisting of Mediterranean Water travels north along the Portuguese continental slope at a depth of about 1000 meters. However, this is much too deep to account for this current (Ivers, 1975).

2. The Circulation Pattern of the Intermediate Water

In making the comparison of this general circulation pattern (Figure 21) with previous studies, a paucity of quantitative transport

information was found to exist for the intermediate waters. It is only with Jung's (1955) study that a comprehensive quantitative analysis was found. Worthington's (1976) work, although more recent, is much more limited in its scope, dealing principally with the two major anticyclonic gyres of the North Atlantic. The coverage of the intermediate circulation by Sverdrup et al. (1942) is limited to a brief descriptive discussion. Therefore the following discussion will, of necessity, be more qualitative in nature with quantitative comparisons made whenever possible.

The region between 8°N and 16°N is found to be dominated by the northward flow of 6.9 units of Antarctic Influence Water which is more than three times that proposed by Jung (1955). Sverdrup's model depicting Antarctic Intermediate Water flowing north along the coast of South America and eventually joining the Gulf Stream contrasts to the computed southward flow of 2.3 units with no Antarctic Influence Water penetrating the 16°N section in this locale.

A possible explanation for this rather abrupt termination is the strong zone of convergence found between 16°N and 24°N latitude. This convergence results in 10.7 units, predominantly Antarctic influence Water, sinking to the Deep and Bottom Water. This area of loss is supported by Jung (1955) who indicates losses of 1.45 units to the Deep and Bottom Water and 1.97 units to the North Atlantic Central Water.

North of 24°N the circulation pattern becomes rather obscure. After careful examination, however, it is found to consist of three large and complex anticyclonic gyres and a very weak northward flow associated with the Gulf Stream.

As the Antilles Current crosses 24°N , 0.8 units are lost to southward flow, with another 0.5 units entrained in an area of active upwelling. The remaining 1.3 units continues north, eventually becoming

the intermediate level Gulf Stream. This value is found to be in sharp contrast to the 17 units and 21sv proposed by Jung (1955) and Worthington (1976). As the Gulf Stream passes 36°N , the flow divides forming zonal and northeasterly components. The zonal component extends east to 55°W longitude at which point it alters to a southerly flow. Although this appears to be forming a return mechanism from the Gulf Stream, the return flow is never completed. The southward flowing water enters an area of convergence and upwelling where it rises to join the Upper Water. The northeasterly component continues until joining the northern anticyclonic gyre along the 48°N section.

The first of the three aforementioned gyres is a small closed anticyclone located in the western-most portion of the 40°N latitude section. Although its transport, 0.6 units, is less than the 3sv indicated for Worthington's gyre, its physical size and location are nearly identical.

The second of the anticyclonic gyres incorporates the majority of the flow across the 48°N latitude section. The flow involves 4.1 units, little more than half of Worthington's value, of which 2.7 units are supplied by the Gulf Stream and Mediterranean Waters. Although the northern extent of this gyre cannot be determined for further comparison, the southern limit matches reasonably well with Worthington's northern gyre.

The last and most extensive of the Intermediate Water gyres is that associated with the circulation of the Mediterranean Waters. In contrast to the simple flow pattern proposed by Sverdrup et al. (1942), Figure 188, a complex anticyclonic gyre composed of many smaller eddies was found extending from the Iberian coast to 55°W and from 40°N to 30°N . Upon sinking the Mediterranean Water is distributed to the west, north, and south by this extensive system of eddies accounting for the presence of

Mediterranean Intermediate Water and/or Mediterranean Influence Water over a large percentage of the North Atlantic Ocean (see Figures 9 through 15). The distribution pattern resulting from this type of circulation is well supported by Worthington (1976), Figure 23, depicting salinity along the 6°C isothermal surface in the North Atlantic.

Again, it must be made clear that the numerous areas of sinking and upwelling have been determined principally by the need to maintain mass continuity.

3. The Circulation Pattern of the Deep and Bottom Water

In conducting an investigation of the deep circulation of the oceans, one finds a myriad of contrasting, and in many cases conflicting, interpretations of circulation patterns and transport values. The pattern proposed in this study attempts to provide a reasonable and geostrophically-consistent solution based on the given data.

The dominant feature of the circulation pattern proposed for the Deep and Bottom Water (Figure 22) is the intense southward transport along the western boundary of the ocean. Appearing as the converse of the surface and intermediate Gulf Stream, the flow is formed by the union of a south-westerly flow of 20.5 units from the Labrador Sea, and a zonal component of 21.9 units. On passing south of 36°N the flow is greatly reduced losing 11.6 units to a return gyre, and 13.6 units to an area of turbulent flow and upwelling. The flow continues south along the South American coast, eventually transporting 13.2 units south of 8°N latitude.

This pattern is in direct contradiction to that depicted by Worthington (1976), Figure 11, who has proposed a large anticyclonic gyre extending from 32°N to 40°N and from 75°W to 45°W transporting 62sv to the north, with a

weaker countercurrent of 6sv inshore of the gyre. Schmitz (1977), in commenting on this circulation scheme, points out that Worthington's pattern is somewhat doubtful due to its violation of geostrophic balance. Schmitz also indicates that moored instrument data have revealed that a northeastward flow is in fact present but located 100-200 km south of the position indicated by Worthington, with a deep strong countercurrent under the axis of the Gulf Stream. Schmitz thus supports the results of this study which indicates a northeastward flow exists seaward of the Gulf Stream from 24°N to 40°N .

The strongest support for this study's flow pattern from 65°W to the western boundary is found in Figure 23 from Tucholke, Wright, and Hollister (1973). This figure is a summary of actual current measurements and photographic evidence of bottom currents. Close comparison of this figure with the circulation pattern of Deep and Bottom Water proposed in this study shows a remarkable degree of correlation.

As we continue eastward, we see the remainder of the Deep and Bottom Water circulation pattern appears as an extensive system of cyclonic and anticyclonic eddies with little or no large-scale coherent current pattern. However, two additional features are present that find support, or at least mention, in previous works. The first, found in the Central North Atlantic in the region of 48°N , 45°W , is a southward flow of North Atlantic Deep Water penetrating south of 24°N . This flow is found to be nearly identical to Defant's (1941) "Middle Branch" of deep water that flows along the eastern slope of the Mid-Atlantic Ridge. The second feature is the large anticyclonic gyre located between 24°N and 32°N , and extending from 70°W to 45°W . Although not directly supported, Schmitz (1977) indicates that moored data from 60°W hints at the existence of a weak deep easterly flow or a closed gyre in this location.

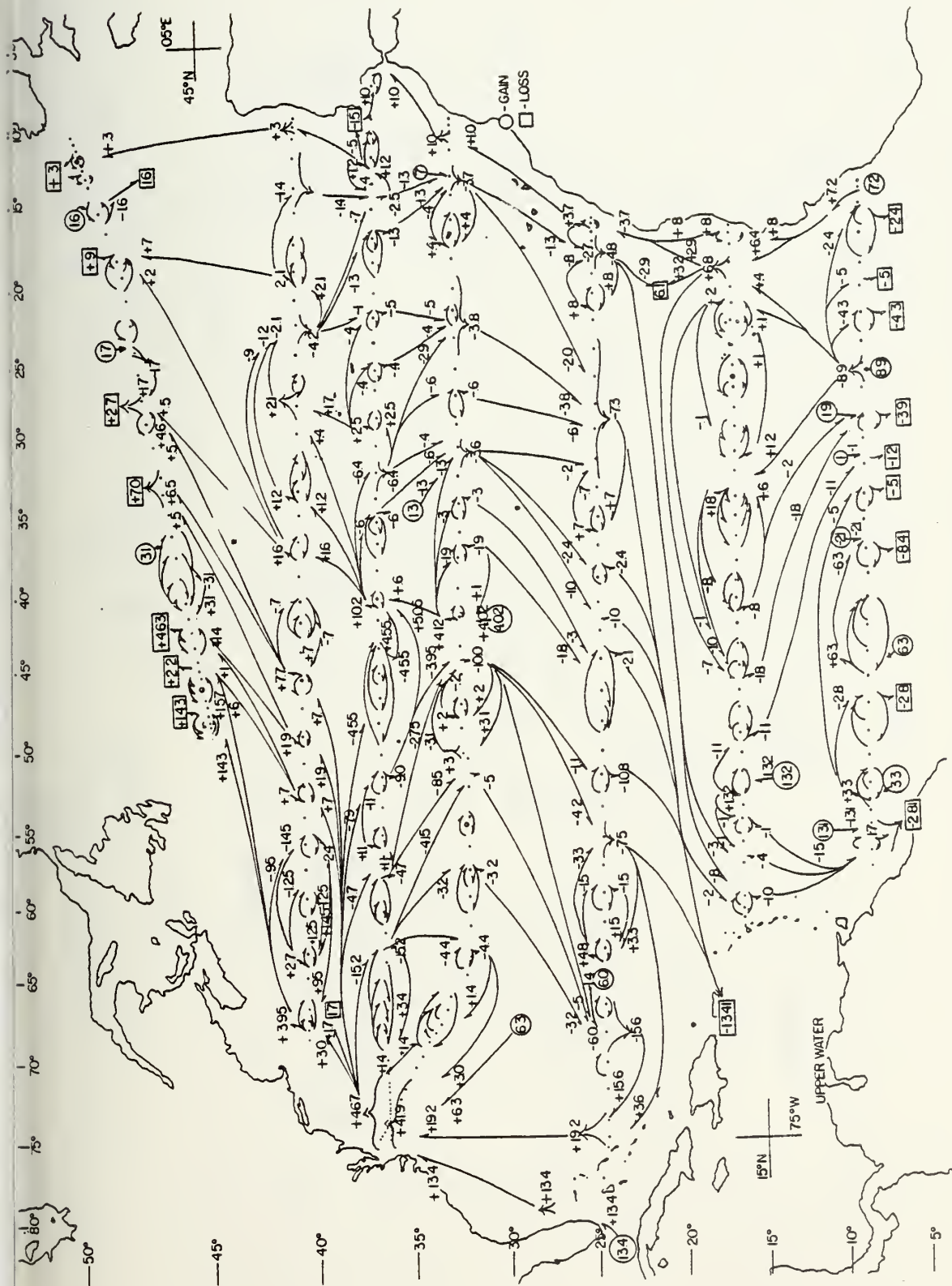


Figure 20. General Circulation Pattern - Upper Water

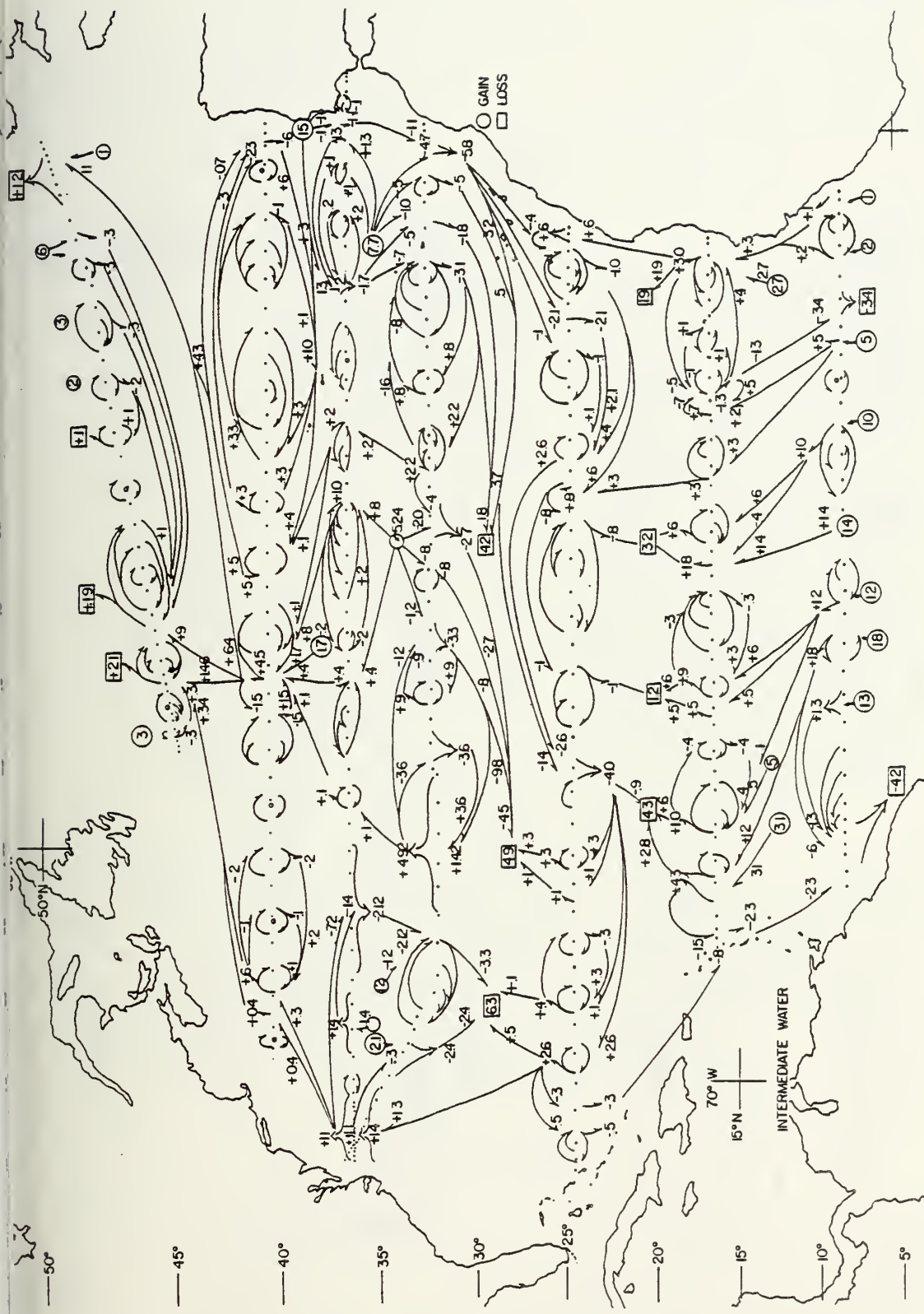


Figure 21. General Circulation Pattern - Intermediate Water

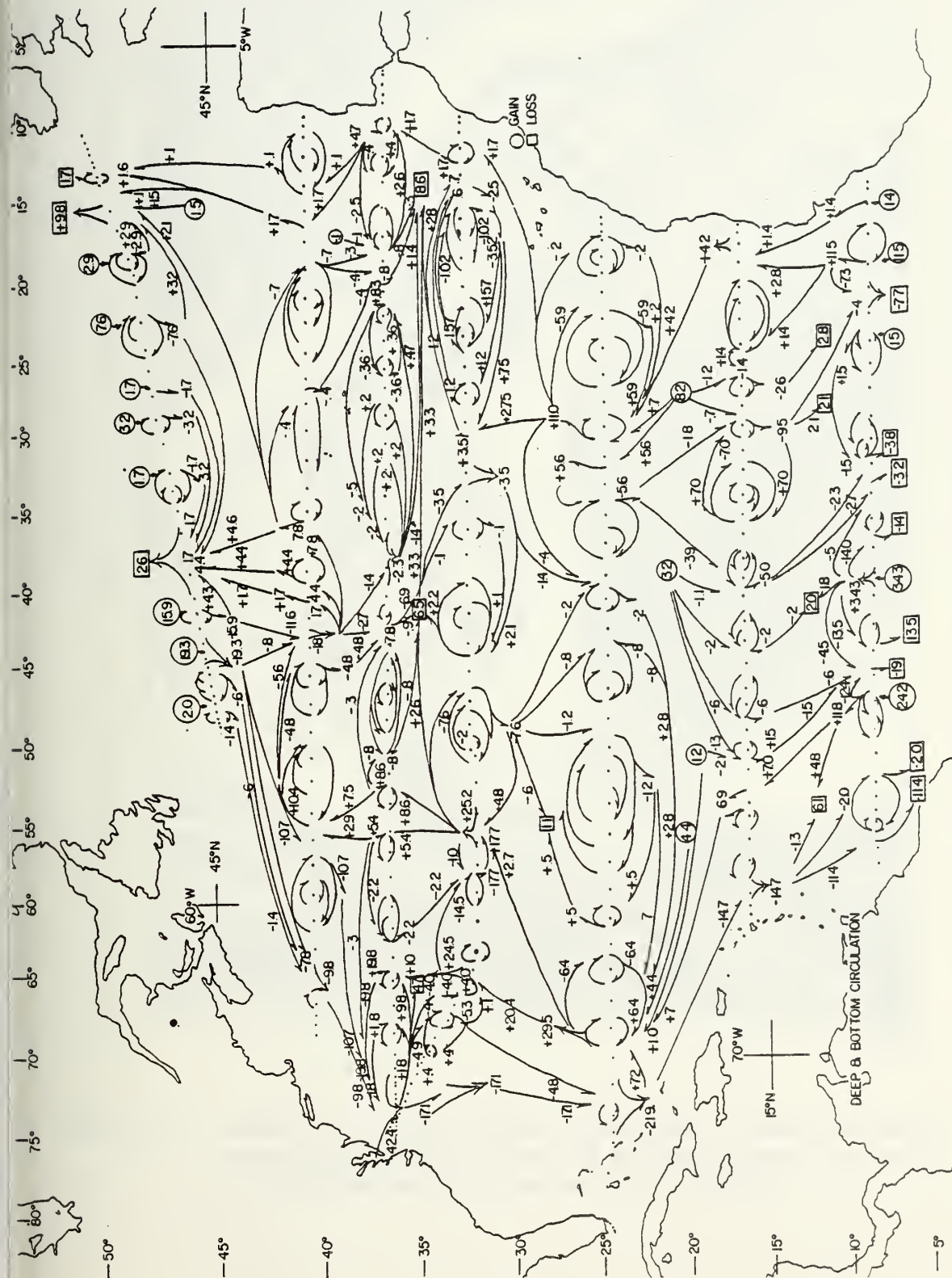


Figure 22. General Circulation Pattern - Deep and Bottom Water



Figure 23. Summary of direct current measurements (white arrows) and photographic evidence of bottom currents according to Tucholke, Wright, and Hollister (1973).

4. A Comparison of Geostrophic and Directly Measured Currents

The circulation patterns presented in the previous sections were predicated upon mass transport values resulting from calculated geostrophic currents. To gain some insight into the degree of correlation that exists between these computed values and directly measured values, the results of a study conducted by Cummings (1977) are introduced.

Cummings, using these same I.G.Y. data, conducted probably the most extensive comparison to date of geostrophic and directly measured currents. Using 110 direct current values extending from 16°N to 40°N , Cummings found extremely encouraging results: 54% showed agreement in both magnitude and direction; 21% showed agreement in direction but not magnitude; and 25% showed no agreement in either category. As an addendum, Cummings stated that of these 110 values, only 25 occurred during the period of this study, 1955-1959; of these, 19 (76%) agreed in both magnitude and direction; 4 (16%) agreed in direction only; and 2 (8%) showed no agreement.

To determine the degree of correlation between the geostrophic velocities of Cummings' study and those of this study, a comparison of the mass transport values of the two works was made. The results of this comparison, contained in Table X, shows that a 90% overall correlation exists between the two works. It should be pointed out, however, that a higher degree of correlation most likely exists since Cummings' work computed mass transport values for only two layers, that above and below the level of no motion. Therefore, in relating those two layers to the three layers of this study, the comparison could be done only for the two most representative layers, namely the Upper, and Deep and Bottom Water, thereby eliminating the mass transport values of the Intermediate Water.

The high degree of correlation that exists between Cummings' work and the present study allows the assumption to be made that the geostrophic calculations and the resulting circulation pattern of this study are well supported by actual current observations.

TABLE X

COMPARISON OF MASS TRANSPORT VALUES OF THIS STUDY
WITH THOSE COMPUTED BY CUMMINGS (1977)*

| LAT. | NO. OF STATION PAIRS | WATER LAYER | AGREEMENT IN MAGNITUDE AND DIRECTION | % | AGREEMENT IN DIRECTION BUT NOT MAGNITUDE | % | NO ** AGREEMENT | % |
|-------|----------------------------|------------------|--------------------------------------------|------|------------------------------------------------|------|--------------------|------|
| 40°N | 37 | Upper | 27 | 73% | 10 | 27% | 0 | 0% |
| | 37 | D+B ⁺ | 36 | 97% | 1 | 3% | 0 | 0% |
| 36°N | 59 | Upper | 58 | 98% | 1 | 2% | 0 | 0% |
| | 59 | D+B | 57 | 97% | 1 | 2% | 1 | 2% |
| 32°N | 53 | Upper | 52 | 98% | 1 | 2% | 0 | 0% |
| | 53 | D+B | 47 | 89% | 6 | 11% | 0 | 0% |
| 27°N | 9 | Upper | 9 | 100% | 0 | 0% | 0 | 0% |
| 24°N | 37 | Upper | 35 | 95% | 1 | 2.5% | 1 | 2.5% |
| | 37 | D+B | 29 | 78% | 7 | 19% | 1 | 3% |
| 16°N | 35 | Upper | 33 | 94% | 0 | 0% | 2 | 6% |
| | 35 | D+B | 26 | 74% | 9 | 26% | 0 | 0% |
| TOTAL | 451 | | 409 | 91% | 37 | 8% | 5 | 1% |

* Positive agreement criterion was established as $\pm 2 \times 10^{12}$ gm/sec with no change in direction.

** No agreement was considered to exist if no directional correlation existed.

+ D+B = Deep and Bottom Water

VI. CONCLUSIONS

This study represents the culmination of a series of three papers dealing with the I.G.Y. data for the North Atlantic Ocean. Using procedures pioneered by Jung (1955), this work attempted to determine:

(1) a level of no meridional motion based on the principles of mass and salt conservation; (2) the effect of the bottom peripheral areas on the net heat transport of the North Atlantic; and (3) a circulation pattern for the three layers of water from computed mass transport values that are consistent with the geostrophic assumption and the continuity of mass.

A level of no motion was determined that lies near 1100m throughout the North Atlantic based on the procedures of Sverdrup et al. (1942). It was also established that there is no definite correlation between this level and any specific isothermal or isohaline surfaces.

In the comparisons of the net meridional heat transports with those of other studies (Figure 19), it was seen that the inclusion of the heat transported in the bottom peripheral areas did not affect the overall net heat flux to any appreciable degree. It can be stated, however, that the meridional heat transport during the I.G.Y. was anomalously low.

The general circulation patterns from this study, as previously stated, do not hope to reflect all aspects of the unique circulation of the North Atlantic Ocean; but they do portray a detailed and quasi-synoptic representation of the geostrophic currents within the ocean which are responsible for the net flux of heat during the given data period.

APPENDIX A

GEOSTROPHIC DATA

The following pages contain the net mass transport values for the Upper, Intermediate, and Deep and Bottom Waters of each pair of stations contained in the seven latitude sections of this study. All mass transport values are in terms of 10^{12} gm/sec.

The following abbreviations are used throughout:

Upper Water:

SFC = Surface Water

NAC = North Atlantic Central Water

SAC = South Atlantic Central Water

Intermediate Water:

AIW = Antarctic Influence Water

NAI = North Atlantic Intermediate Water

MIW = Mediterranean Influence Water

MED = Mediterranean Intermediate Water

Deep and Bottom Water:

NAD= North Atlantic Deep Water

8°N UPPER WATER

| STAT NO. | STAT TOTAL | SFC | NAC | SAC |
|----------|------------|-----------|----------|----------|
| 184-183 | -.32480 | .3497 | -.3651 | -.30939 |
| 183-182 | 3.37836 | 2.04544 | -.02816 | 1.36108 |
| 182-181 | -5.32287 | -6.08849 | -.66904 | 1.43466 |
| 181-180 | -.80834 | 2.61926 | -.84838 | -2.57922 |
| 180-179 | 4.64607 | 6.11178 | .20446 | -1.67017 |
| 179-178 | 6.51088 | 5.13219 | .81995 | .55874 |
| 178-177 | -7.82134 | -6.66287 | -1.41203 | .25356 |
| 177-176 | .20621 | -1.91179 | .36204 | 1.75596 |
| 176-175 | 2.76941 | .96563 | .26285 | 1.54093 |
| 175-174 | -5.81477 | -.49343 | -.44971 | -4.87163 |
| 174-173 | 7.43579 | 1.18149 | 1.55769 | 4.69661 |
| 173-172 | 3.92033 | 2.49905 | .08053 | 1.34075 |
| 172-171 | .85964 | .69029 | .15914 | .01021 |
| 171-170 | -5.91738 | -3.52636 | -.30088 | -2.09014 |
| 170-169 | 5.62026 | 2.58847 | .50285 | 2.52894 |
| 169-168 | -13.98499 | -11.38228 | -1.04002 | -1.56269 |
| 168-167 | .20855 | -1.61772 | -.1576 | 1.98387 |
| 167-166 | -.65905 | 2.12051 | .47576 | -3.25532 |
| 166-165 | -1.1508 | -.03255 | -.61903 | -.49922 |
| 165-164 | 6.53048 | .3224 | 1.54919 | 4.65889 |
| 164-163 | -10.42494 | -2.6136 | -1.40572 | -6.40562 |
| 163-162 | 4.1658 | 2.57738 | .31313 | 1.27529 |
| 162-161 | 4.76626 | -.02663 | 2.57404 | 2.21885 |
| 161-160 | 2.71238 | .58522 | .81299 | 1.31417 |
| 160-159 | -6.99697 | -1.42063 | -2.03828 | -3.55806 |
| 159-158 | -.51109 | .74823 | .22592 | -1.48524 |
| 158-157 | 5.09587 | -.35991 | 2.19068 | 3.2651 |
| 157-156 | .11789 | 1.60385 | -.12904 | -1.35692 |
| 156-155 | -7.55937 | -3.40879 | -2.77043 | -1.38015 |
| 155-154 | 7.16964 | .64678 | 3.53911 | 2.98375 |
| TOTAL | -1.18289 | | | |

8°N INTERMEDIATE WATER

| STAT NO. | STAT TOTAL | AIW | MIW |
|----------|------------|----------|----------|
| 184-183 | 0.0 | 0.0 | 0.0 |
| 183-182 | -2.8661 | 1.13552 | -4.00162 |
| 182-181 | -.0826 | -1.91447 | 1.83187 |
| 181-180 | -.89814 | -.89814 | 0.0 |
| 180-179 | -1.51636 | -1.51636 | 0.0 |
| 179-178 | .26819 | .26819 | 0.0 |
| 178-177 | .00349 | .34643 | -.34294 |
| 177-176 | .15296 | 1.16702 | -1.01406 |
| 176-175 | .69371 | 1.56759 | -.87388 |
| 175-174 | .5974 | -2.23964 | 2.83704 |
| 174-173 | .66038 | 1.92734 | -1.26696 |
| 173-172 | -2.06395 | 1.27584 | -3.33979 |
| 172-171 | 3.85953 | .11845 | 3.74108 |
| 171-170 | 2.73922 | -.15509 | 2.89431 |
| 170-169 | .78764 | .88727 | -.09963 |
| 169-168 | -2.27535 | .30148 | -2.57683 |
| 168-167 | 1.42611 | .25223 | 1.17388 |
| 167-166 | -.46517 | -.77316 | .30799 |
| 166-165 | -.43354 | .50328 | -.93682 |
| 165-164 | .63247 | .50525 | .12722 |
| 164-163 | 1.27165 | -.35059 | 1.62224 |
| 163-162 | -.75824 | .64709 | -1.40533 |
| 162-161 | .77515 | .71649 | .05866 |
| 161-160 | .48097 | -.02054 | .50153 |
| 160-159 | -.31092 | -.67352 | .3626 |
| 159-158 | -.04039 | -.31075 | .27063 |
| 158-157 | .57567 | .82100 | -.24533 |
| 157-156 | .08379 | -.27526 | .35905 |
| 156-155 | -.49528 | -.23910 | -.25618 |
| 155-154 | .05175 | .05175 | 0.0 |
| TOTAL | 2.85404 | | |

8°N DEEP AND BOTTOM WATER

| <u>STAT NO.</u> | <u>STAT TOTAL (ALL WATER IS NAD)</u> |
|-----------------|----------------------------------------|
| 184-183 | 0.0 |
| 183-182 | -11.40281 |
| 182-181 | 5.62678 |
| 181-180 | -2.06200 |
| 180-179 | 0.0 |
| 179-178 | 0.0 |
| 178-177 | -5.50047 |
| 177-176 | .30760 |
| 176-175 | -8.15742 |
| 175-174 | 32.07795 |
| 174-173 | -18.97981 |
| 173-172 | -32.45529 |
| 172-171 | 18.98081 |
| 171-170 | 33.81475 |
| 170-169 | .46318 |
| 169-168 | -31.22556 |
| 168-167 | 17.21635 |
| 167-166 | -3.17139 |
| 166-165 | -23.51369 |
| 165-164 | 8.36104 |
| 164-163 | 11.37969 |
| 163-162 | -4.08616 |
| 162-161 | -2.87780 |
| 161-160 | 8.46067 |
| 160-159 | -2.80924 |
| 159-158 | -4.90601 |
| 158-157 | 22.83172 |
| 157-156 | -11.33475 |
| 156-155 | 1.35568 |
| 155-154 | 0.0 |
| TOTAL | -1.60618 |

16° N UPPER WATER

| STAT NO. | STAT TOTAL | SFC | NAC | SAC |
|----------|------------|----------|----------|----------|
| 310-309 | .34770 | .33627 | .01143 | 0.0 |
| 309-308 | 5.39426 | .87842 | 3.76160 | .75424 |
| 308-306 | -6.66477 | -3.14138 | -2.74021 | -.78318 |
| 306-305 | -.39526 | -.79918 | .38139 | .02253 |
| 305-304 | 7.56191 | 4.77028 | 2.14307 | .64826 |
| 304-303 | -7.68819 | -5.59720 | -1.87273 | -.18826 |
| 303-302 | 2.52293 | 1.81804 | .65114 | .05375 |
| 302-301 | -1.19017 | -1.34605 | -.04053 | .19641 |
| 301-300 | -2.76900 | -1.97636 | -.56650 | -.22614 |
| 300-299 | 1.33217 | .60332 | .30332 | .42553 |
| 299-298 | .41919 | .62829 | -.08969 | -.11945 |
| 298-297 | -5.76798 | -3.62647 | -1.43627 | -.70524 |
| 297-296 | 3.69650 | 1.71249 | .91145 | 1.07256 |
| 296-295 | .27368 | .05929 | .14799 | .06650 |
| 295-294 | -3.62508 | -2.25465 | -.94982 | -.42061 |
| 294-293 | 1.59223 | .20334 | .90577 | .48312 |
| 293-292 | 1.23317 | .54485 | .26986 | .41844 |
| 292-291 | -1.32984 | -.53624 | -.44680 | -.34680 |
| 291-290 | -.70958 | .30017 | -.53531 | -.47444 |
| 290-289 | -1.11386 | -1.78895 | .23602 | .43907 |
| 289-288 | 4.89943 | 1.21808 | 1.91041 | 1.77094 |
| 288-287 | -.59201 | -.32724 | .05470 | -.31947 |
| 287-286 | -1.94739 | -.69728 | -.96580 | -.28431 |
| 286-285 | 2.36345 | -.19083 | 1.25522 | 1.29906 |
| 285-284 | -4.45934 | -.20978 | -3.03588 | -1.21368 |
| 284-283 | 3.85413 | .93891 | 2.41673 | .49849 |
| 283-282 | .62648 | .33240 | .30148 | -.00740 |
| 282-281 | -3.62958 | -1.30361 | -1.49996 | -.82601 |
| 281-280 | 3.10476 | .37764 | 1.67809 | 1.04903 |
| 280-279 | .68370 | .09192 | .36544 | .22634 |
| 279-278 | 4.56607 | 1.29906 | 2.28174 | .32679 |
| 278-277 | 2.16292 | .63056 | 1.32637 | .20599 |
| 277-276 | -1.39817 | -1.41590 | -.65135 | .66908 |
| 276-275 | .07940 | .07940 | 0.0 | 0.0 |

TOTAL 5.49752*

* This total contains 2.047 mass units contributed by the bottom peripheral area of stations 276-275 not included in the above summary.

16⁰N INTERMEDIATE WATER

| STAT NO. | STAT TOTAL | AIW | MIW |
|----------|------------|---------|----------|
| 310-309 | 0.0 | 0.0 | 0.0 |
| 309-308 | -2.36433 | .37714 | -2.74147 |
| 308-306 | 3.53219 | .93816 | 2.59403 |
| 306-305 | .87399 | .21631 | .65768 |
| 305-304 | -.04480 | .47676 | -.52156 |
| 304-303 | 1.90134 | .15423 | 1.74711 |
| 303-302 | -.47244 | .02610 | -.49854 |
| 302-301 | -.39710 | .01203 | -.40913 |
| 301-300 | .76216 | .01013 | .75203 |
| 300-299 | -1.18890 | .13291 | -1.32181 |
| 299-298 | .50350 | -.00529 | .50879 |
| 298-297 | 1.31333 | -.26468 | 1.57801 |
| 297-296 | -.40753 | .40016 | -.80769 |
| 296-295 | .08828 | .11370 | -.02542 |
| 295-294 | .21514 | -.19236 | .40753 |
| 294-293 | .03596 | .10138 | -.06542 |
| 293-292 | -.58777 | .25037 | -.83714 |
| 292-291 | 1.77032 | -.03379 | 1.80411 |
| 291-290 | 1.57450 | -.12105 | 1.69555 |
| 290-289 | -.15103 | .19912 | -.35015 |
| 289-288 | -.78472 | .44019 | -1.22491 |
| 288-287 | 1.29972 | -.04423 | 1.34395 |
| 287-286 | .07502 | -.01656 | .09158 |
| 286-285 | -1.06783 | .07146 | -1.13929 |
| 285-284 | .64787 | -.10105 | .74892 |
| 284-283 | -2.36351 | 0.0 | -2.36351 |
| 283-282 | 1.10722 | 0.0 | 1.10722 |
| 282-281 | -.25309 | 0.0 | -.25309 |
| 281-280 | .39727 | 0.0 | .39727 |
| 280-279 | -.72795 | 0.0 | -.72795 |
| 279-278 | -.03207 | 0.0 | -.03207 |
| 278-277 | .13633 | 0.0 | .13633 |
| 277-276 | 3.73846 | 0.0 | 3.73846 |
| 276-275 | 0.0 | 0.0 | 0.0 |
| TOTAL | 9.11645 | | |

16°N DEEP AND BOTTOM WATER

| <u>STAT NO.</u> | <u>STAT TOTAL (ALL WATER IS NAD)</u> |
|-----------------|--------------------------------------|
| 310-309 | 0.0 |
| 309-308 | -11.86731 |
| 308-306 | -18.87209 |
| 306-305 | 16.06306 |
| 305-304 | -7.72756 |
| 304-303 | 7.84082 |
| 303-302 | 6.85646 |
| 302-301 | -7.03319 |
| 301-300 | 5.57014 |
| 300-299 | -7.29519 |
| 299-298 | 2.11222 |
| 298-297 | 4.64007 |
| 297-296 | -12.39570 |
| 296-295 | 2.86841 |
| 295-294 | 9.27541 |
| 294-293 | -12.24428 |
| 293-292 | -4.48943 |
| 292-291 | 11.78491 |
| 291-290 | 21.68922 |
| 290-289 | 7.97124 |
| 289-288 | -9.46687 |
| 288-287 | -13.26967 |
| 287-286 | 3.78026 |
| 286-285 | -13.31789 |
| 285-284 | 13.96027 |
| 284-283 | -16.57470 |
| 283-282 | 4.93409 |
| 282-281 | 0.0 |
| 281-280 | 0.0 |
| 280-279 | -2.97441 |
| 279-278 | -.48774 |
| 278-277 | 1.27340 |
| 277-276 | 2.91500 |
| 276-275 | 0.0 |
| TOTAL | -14.48235 |

24° N UPPER WATER

| STAT NO. | STAT TOTAL | SFC | NAC |
|-----------|------------|----------|----------|
| 3624-3623 | .29845 | -.86167 | 1.16012 |
| 3623-3622 | 3.38121 | 3.24083 | .14038 |
| 3622-3621 | 15.50684 | 10.45671 | 5.05013 |
| 3621-3620 | .39388 | -.09491 | .48879 |
| 3620-3619 | -9.95086 | -7.06233 | -2.88853 |
| 3619-3618 | 1.27708 | .79817 | .47891 |
| 3618-3617 | -7.27175 | -5.61016 | -1.66159 |
| 3617-3616 | 7.71168 | 5.34272 | 2.36896 |
| 3616-3615 | -2.88011 | -2.22091 | -.65920 |
| 3615-3614 | 1.04967 | .57133 | .47834 |
| 3614-3613 | -2.50160 | -1.79955 | -.70205 |
| 3613-3612 | -3.04990 | -2.46167 | -.58823 |
| 3612-3611 | -4.43060 | -2.95456 | -1.47604 |
| 3611-3610 | 2.32944 | 1.70473 | .62471 |
| 3610-3609 | -3.36373 | -2.73383 | -.62990 |
| 3609-3608 | 3.66237 | 2.69897 | .96340 |
| 3608-3607 | -1.17248 | -1.21386 | .04133 |
| 3607-3606 | -.85913 | -.58475 | -.27438 |
| 3606-3605 | -3.93210 | -2.90018 | -1.03192 |
| 3605-3604 | -1.03951 | -.32555 | -.71396 |
| 3604-3603 | 1.58159 | .47600 | 1.10559 |
| 3603-3602 | -3.95641 | -2.19684 | -1.75957 |
| 3602-3601 | 2.11601 | 1.07806 | 1.03795 |
| 3601-3600 | -1.41678 | -1.03215 | -.38463 |
| 3600-3599 | -1.12176 | -.44489 | -.67687 |
| 3599-3598 | -1.65708 | -1.15832 | -.49876 |
| 3598-3597 | -.31895 | -.10022 | -.21873 |
| 3597-3596 | -1.00327 | -.80739 | -.19588 |
| 3596-3595 | -2.67481 | -1.53620 | -1.13861 |
| 3595-3594 | -.46873 | -.34400 | -.12473 |
| 3594-3593 | 2.32844 | .84761 | 1.48083 |
| 3593-3592 | -1.49438 | -.90897 | -.58541 |
| 3592-3591 | -.15900 | -.16654 | .00754 |
| 3591-3590 | -1.49210 | -.97980 | -.51230 |
| 3590-3589 | -2.93181 | -1.39728 | -1.53453 |
| 3589-3588 | 3.79237 | 1.48959 | 2.30278 |
| 3588-3587 | -.03892 | -.03892 | 0.0 |
| TOTAL | -14.11674 | | |

24° N INTERMEDIATE WATER

| STAT NO. | STAT TOTAL | MIW | MED |
|-----------|------------|----------|---------|
| 3624-3623 | .18976 | .18976 | 0.0 |
| 3623-3622 | .20823 | .20823 | 0.0 |
| 3622-3621 | -.93935 | -.93935 | 0.0 |
| 3621-3620 | -.26321 | -.26321 | 0.0 |
| 3620-3619 | 2.83645 | 2.83645 | 0.0 |
| 3619-3618 | -.23515 | -.23515 | 0.0 |
| 3618-3617 | 1.55946 | 1.55946 | 0.0 |
| 3617-3616 | -1.21845 | -1.21845 | 0.0 |
| 3616-3615 | .48669 | .48669 | 0.0 |
| 3615-3614 | -.82912 | -.82912 | 0.0 |
| 3614-3613 | .05045 | .05045 | 0.0 |
| 3613-3612 | .50000 | .50000 | 0.0 |
| 3612-3611 | -.17095 | -.17095 | 0.0 |
| 3611-3610 | .01347 | .01347 | 0.0 |
| 3610-3609 | -3.23184 | -3.23184 | 0.0 |
| 3609-3608 | -.82703 | -.82703 | 0.0 |
| 3608-3607 | 2.89328 | 2.89328 | 0.0 |
| 3607-3606 | -2.84478 | -2.84015 | -.00463 |
| 3606-3605 | -.17866 | -.05211 | -.12655 |
| 3605-3604 | 1.57195 | 1.67757 | -.10562 |
| 3604-3603 | -.93753 | -1.08242 | .14489 |
| 3603-3602 | 2.63124 | 2.95798 | -.32674 |
| 3602-3601 | -1.34929 | -1.45094 | .10165 |
| 3601-3600 | -2.48478 | -2.54483 | .06005 |
| 3600-3599 | .88008 | .94669 | -.06661 |
| 3599-3598 | 4.29027 | 4.39826 | -.10799 |
| 3598-3597 | -1.64690 | -1.66892 | .02202 |
| 3597-3596 | 1.37962 | 1.42530 | -.04568 |
| 3596-3595 | .50733 | .59981 | -.09248 |
| 3595-3594 | -1.98821 | -2.08747 | .09926 |
| 3594-3593 | -2.06235 | -2.17584 | .11349 |
| 3593-3592 | .56153 | .60203 | -.04050 |
| 3592-3591 | .76311 | .77637 | -.01326 |
| 3591-3590 | -1.28938 | -1.28938 | 0.0 |
| 3590-3589 | -1.14159 | -1.14159 | 0.0 |
| 3589-3588 | .04502 | .04502 | 0.0 |
| 3588-3587 | .55429 | .55429 | 0.0 |
| TOTAL | -1.71634 | | |

24°N DEEP AND BOTTOM WATER

| <u>STAT NO.</u> | <u>STAT TOTAL (ALL WATER IS NAD)</u> |
|-----------------|----------------------------------------|
| 3624-3623 | -.51525 |
| 3623-3622 | -17.19300 |
| 3622-3621 | 6.48019 |
| 3621-3620 | -10.69333 |
| 3620-3619 | 40.28519 |
| 3619-3618 | -10.80161 |
| 3618-3617 | 23.72204 |
| 3617-3616 | -30.10491 |
| 3616-3615 | 12.09790 |
| 3615-3614 | -11.56423 |
| 3614-3613 | 3.54576 |
| 3613-3612 | 5.55202 |
| 3612-3611 | 3.83257 |
| 3611-3610 | -.32115 |
| 3610-3609 | -12.81473 |
| 3609-3608 | -1.13451 |
| 3608-3607 | 3.09145 |
| 3607-3606 | -2.79427 |
| 3606-3605 | -1.13130 |
| 3605-3604 | 5.28338 |
| 3604-3603 | -7.32353 |
| 3603-3602 | 16.71581 |
| 3602-3601 | -8.66357 |
| 3601-3600 | -13.68396 |
| 3600-3599 | 5.60559 |
| 3599-3598 | 15.14507 |
| 3598-3597 | -4.07922 |
| 3597-3596 | 4.66236 |
| 3596-3595 | 2.80469 |
| 3595-3594 | -7.69124 |
| 3594-3593 | -5.64486 |
| 3593-3592 | 1.56596 |
| 3592-3591 | .26493 |
| 3591-3590 | -1.35405 |
| 3590-3589 | -.69033 |
| 3589-3588 | 0.0 |
| 3588-3587 | 0.0 |
| TOTAL | 2.45586 |

27° N UPPER WATER

| STAT NO. | STAT TOTAL | SFC | NAC |
|-----------|------------|---------|---------|
| 5343-5342 | .13942 | .13942 | 0.0 |
| 5342-5341 | .50616 | .46458 | .04159 |
| 5341-5340 | .93047 | .74721 | .18326 |
| 5340-5339 | 2.15102 | 1.82379 | .32723 |
| 5339-5338 | 2.73575 | 2.17764 | .55811 |
| 5338-5337 | 5.22364 | 3.74867 | 1.47497 |
| 5337-5336 | .64035 | -.30703 | .94738 |
| 5336-5335 | .93804 | .85477 | .08327 |
| 5335-5334 | .08872 | .08872 | 0.0 |
| TOTAL | 13.35357 | | |

32°N UPPER WATER

| STAT NO. | STAT TOTAL | SFC | NAC |
|-----------|------------|-----------|----------|
| 5293-5294 | .02976 | .02976 | 0.0 |
| 5294-5295 | -.20966 | -.20966 | 0.0 |
| 5295-5296 | .63670 | .44328 | .19342 |
| 5296-5297 | 1.89598 | 1.24678 | .64920 |
| 5297-5298 | 4.75840 | 1.95149 | 2.80691 |
| 5298-5299 | 22.31201 | 10.09817 | 12.21384 |
| 5299-5301 | 22.18105 | 5.86380 | 16.31725 |
| 5301-5302 | 4.40468 | 2.98447 | 1.42021 |
| 5302-5303 | 2.94194 | 2.27507 | .66687 |
| 5303-5304 | -1.06250 | -.32296 | -.73954 |
| 5304-5305 | -7.57239 | -6.24843 | -1.32396 |
| 5305-5306 | -5.00832 | -3.89252 | -1.11580 |
| 5306-5307 | -3.41771 | -2.36590 | -1.05181 |
| 5307-5308 | 10.62174 | 7.90705 | 2.71468 |
| 5308-5309 | .95512 | .74170 | .21342 |
| 5309-5310 | 1.44368 | 1.12902 | .31466 |
| 5310-5311 | 4.98524 | 4.09717 | .88807 |
| 5311-5312 | -12.13440 | -9.74656 | -2.38784 |
| 5312-5564 | -4.53284 | -3.04284 | -1.49000 |
| 5564-5203 | 2.09002 | 1.92367 | .16635 |
| 5203-5204 | -6.52051 | -4.97519 | -1.54532 |
| 5204-5205 | 10.32867 | 7.34940 | 2.97927 |
| 5205-5206 | .40475 | .76413 | -.35938 |
| 5206-5207 | -13.90942 | -10.47902 | -3.43040 |
| 5207-5208 | 3.92797 | 2.95398 | .97399 |
| 5208-5209 | -3.86884 | -2.38756 | -1.48128 |
| 5209-5210 | -5.01550 | -3.43319 | -1.58231 |
| 5210-3625 | 2.38197 | 1.49869 | .88328 |
| 3625-3626 | .72253 | .06318 | .65935 |
| 3626-3627 | 3.36381 | 1.80013 | 1.56368 |
| 3627-3628 | -3.17552 | -1.37158 | -1.80394 |
| 3628-3629 | -9.97327 | -6.04966 | -3.92361 |
| 3629-3630 | 5.67104 | 3.33868 | 2.33236 |
| 3630-3631 | -1.58173 | -1.20971 | -.37202 |
| 3631-3632 | .71572 | .93615 | -.22043 |
| 3632-3633 | -2.59478 | -2.38538 | -.20940 |
| 3633-3634 | .69865 | .50516 | .19349 |
| 3634-3635 | -.95131 | -.81745 | -.13386 |
| 3635-3636 | -.44661 | -.23597 | -.21064 |
| 3636-3637 | -3.22584 | -1.25925 | -1.96659 |
| 3637-3638 | 1.56640 | .93808 | .62832 |
| 3638-3639 | -2.26965 | -1.33136 | -.93829 |
| 3639-3640 | -1.15142 | -.56128 | -.59014 |
| 3640-3641 | .12471 | -.10411 | .22882 |
| 3641-3642 | -2.27938 | -1.13049 | -1.14889 |
| 3642-3643 | -.43450 | -.27069 | -.16381 |
| 3643-3644 | 1.23166 | .49549 | .73617 |
| 3644-3645 | -.78854 | -.56856 | -.21998 |
| 3645-3646 | -1.93153 | -.36000 | -1.57153 |
| 3646-3647 | -1.77553 | -.74527 | -1.03026 |
| 3647-3648 | .66468 | .42725 | .23743 |
| 3648-3649 | .27891 | .18725 | .09166 |
| 3649-3650 | 0.0 | 0.0 | 0.0 |
| TOTAL | 15.50609 | | |

32°N INTERMEDIATE WATER

| STAT NO. | STAT TOTAL | MIW | MED |
|-----------|------------|----------|----------|
| 5293-5294 | 0.0 | 0.0 | 0.0 |
| 5294-5295 | .08775 | .08775 | 0.0 |
| 5295-5296 | .10971 | .10971 | 0.0 |
| 5296-5297 | .40516 | .40516 | 0.0 |
| 5297-5298 | .93623 | .93623 | 0.0 |
| 5298-5299 | 1.83973 | 1.83973 | 0.0 |
| 5299-5301 | -.60331 | -.60331 | 0.0 |
| 5301-5302 | -1.89340 | -1.89340 | 0.0 |
| 5302-5303 | -.77625 | -.77625 | 0.0 |
| 5303-5304 | .25336 | .25336 | 0.0 |
| 5304-5305 | .52083 | .52083 | 0.0 |
| 5305-5306 | .32049 | .32049 | 0.0 |
| 5306-5307 | .06405 | .06405 | 0.0 |
| 5307-5308 | -.42450 | -.42450 | 0.0 |
| 5308-5309 | -.84165 | -.84165 | 0.0 |
| 5309-5310 | -.41493 | -.41493 | 0.0 |
| 5310-5311 | -.55318 | -.55318 | 0.0 |
| 5311-5312 | 2.90975 | 3.03106 | -.12131 |
| 5312-5564 | .53183 | .53183 | 0.0 |
| 5564-5203 | -.31041 | -.30277 | -.00764 |
| 5203-5204 | -.09471 | .03465 | -.12936 |
| 5204-5205 | -6.31716 | -6.49939 | .18213 |
| 5205-5206 | 2.15106 | 2.15106 | 0.0 |
| 5206-5207 | .99082 | .99082 | 0.0 |
| 5207-5208 | .27939 | .27939 | 0.0 |
| 5208-5209 | .51552 | .51552 | 0.0 |
| 5209-5210 | .60868 | .60868 | 0.0 |
| 5210-3625 | .30462 | .30462 | 0.0 |
| 3625-3626 | -2.57434 | -2.67826 | .10392 |
| 3626-3627 | -.90421 | -1.09767 | .19346 |
| 3627-3628 | 1.33164 | 1.50995 | -.17831 |
| 3628-3629 | -.37857 | -.21603 | -.16254 |
| 3629-3630 | -3.12045 | -3.42810 | .30765 |
| 3630-3631 | -.17600 | -.21114 | .03514 |
| 3631-3632 | .34905 | .57149 | -.22244 |
| 3632-3633 | -1.24906 | -1.37161 | .12255 |
| 3633-3634 | -1.23445 | -1.23270 | -.00175 |
| 3634-3635 | -1.50267 | -1.16858 | -.33409 |
| 3635-3636 | 2.32751 | 1.96618 | .36133 |
| 3636-3637 | .16193 | .31455 | -.15262 |
| 3637-3638 | -.31336 | -.39505 | .08169 |
| 3638-3639 | 1.52485 | 1.54960 | -.02475 |
| 3639-3640 | -.69881 | -.51739 | -.18142 |
| 3640-3641 | .50535 | .38677 | .11858 |
| 3641-3642 | .19878 | .29488 | -.09610 |
| 3642-3643 | 1.21633 | 1.19386 | .02247 |
| 3643-3644 | -4.96106 | -3.29546 | -1.66560 |
| 3644-3645 | -1.80010 | -1.15766 | -.64244 |
| 3645-3646 | 2.20254 | 2.04158 | .16096 |
| 3646-3647 | -2.70624 | -1.87863 | -.82761 |
| 3647-3648 | -5.17714 | -2.20369 | -2.97345 |
| 3648-3649 | -.05630 | 0.0 | -.05630 |
| 3649-3650 | 0.0 | 0.0 | 0.0 |

TOTAL -16.98194*

*Total contains -.54664 mass units from bottom area of stations 3648-3649 not included in the above summary.

32°N DEEP AND BOTTOM WATER

| STAT NO. | STAT TOTAL (ALL WATER IS NAD) |
|-----------|---------------------------------|
| 5293-5294 | 0.0 |
| 5294-5295 | -.14073 |
| 5295-5296 | -.35281 |
| 5296-5297 | -.00427 |
| 5297-5298 | -1.00934 |
| 5298-5299 | -3.07328 |
| 5299-5301 | -6.65255 |
| 5301-5302 | -9.93086 |
| 5302-5303 | -3.50470 |
| 5303-5304 | -.27033 |
| 5304-5305 | 7.56952 |
| 5305-5306 | .28872 |
| 5306-5307 | 3.84289 |
| 5307-5308 | -3.37894 |
| 5308-5309 | 1.96654 |
| 5309-5310 | -7.29261 |
| 5310-5311 | -3.95432 |
| 5311-5312 | 24.53632 |
| 5312-5564 | 3.30069 |
| 5564-5203 | -3.38433 |
| 5203-5204 | 9.92456 |
| 5204-5205 | -27.62533 |
| 5205-5206 | 11.99174 |
| 5206-5207 | 10.38506 |
| 5207-5208 | 2.77542 |
| 5208-5209 | 2.52036 |
| 5209-5210 | 6.13964 |
| 5210-3625 | -1.97510 |
| 3625-3626 | -10.96918 |
| 3626-3627 | -3.20511 |
| 3627-3628 | 4.73687 |
| 3628-3629 | 2.27673 |
| 3629-3630 | -4.31168 |
| 3630-3631 | -.50523 |
| 3631-3632 | 1.50072 |
| 3632-3633 | -1.58014 |
| 3633-3634 | -1.92638 |
| 3634-3635 | -1.55010 |
| 3635-3636 | 3.45122 |
| 3636-3637 | 1.72430 |
| 3637-3638 | +.43513 |
| 3638-3639 | 2.73125 |
| 3639-3640 | -.82500 |
| 3640-3641 | -.32340 |
| 3641-3642 | .82914 |
| 3642-3643 | 5.45383 |
| 3643-3644 | -7.32136 |
| 3644-3645 | -2.46785 |
| 3645-3646 | 5.15309 |
| 3646-3647 | -2.54292 |
| 3647-3648 | -1.06637 |
| 3648-3649 | 0.0 |
| 3649-3650 | 0.0 |

TOTAL 1.51926

36°N UPPER WATER

| STAT NO. | STAT TOTAL | SFC | NAC |
|----------|------------|-----------|-----------|
| 18-19 | -.03601 | -.03601 | 0.0 |
| 19-20 | .14504 | .07040 | .07464 |
| 20-21 | -.92198 | -.36333 | -.55864 |
| 21-22 | 1.14382 | .80194 | .34188 |
| 22-23 | -.99780 | -.52709 | -.47071 |
| 23-24 | -.28286 | -.16570 | -.11716 |
| 24-25 | -.47079 | -.42929 | -.04150 |
| 25-26 | .40873 | .40522 | .00351 |
| 26-27 | .42862 | .24804 | .18054 |
| 27-28 | 1.79916 | 1.16361 | .63555 |
| 28-29 | 4.81280 | 2.31438 | 2.49842 |
| 29-30 | 19.82719 | 6.23256 | 13.59463 |
| 30-31 | 13.79654 | 9.25528 | 4.54126 |
| 31-32 | -14.81871 | -10.44710 | -4.37161 |
| 32-33 | 21.91861 | 13.09026 | 8.82835 |
| 33-34 | 15.96383 | 12.71794 | 3.24589 |
| 34-35 | -3.45635 | -3.45123 | -.00512 |
| 35-36 | -1.30261 | -.74899 | -.55362 |
| 36-37 | -3.23962 | -2.22475 | -1.01487 |
| 37-38 | -22.89120 | -15.73201 | -7.15919 |
| 38-39 | 18.93819 | 12.28772 | 6.65047 |
| 39-40 | -6.54181 | -4.55049 | -1.99132 |
| 40-41 | -17.06665 | -10.46823 | -6.59842 |
| 41-42 | 2.96643 | 1.37034 | 1.59609 |
| 42-43 | -1.91020 | -1.04900 | -.86120 |
| 43-44 | 1.63104 | .97921 | .65183 |
| 44-45 | -10.59629 | -5.39943 | -5.19686 |
| 45-46 | 13.83881 | 6.74651 | 7.09230 |
| 46-47 | 12.61871 | 7.63479 | 4.98392 |
| 47-48 | 13.55607 | 9.85415 | 3.70192 |
| 48-49 | -16.37634 | -11.38845 | -4.98789 |
| 49-50 | -28.08490 | -11.89505 | -16.18985 |
| 50-51 | 14.41843 | 4.08020 | 10.33823 |
| 51-52 | -4.27903 | -2.78979 | -1.48925 |
| 52-53 | 2.50956 | 1.23884 | 1.27072 |
| 53-54 | 3.48090 | 1.56127 | 1.91963 |
| 54-55 | -6.62879 | -3.00458 | -3.62421 |
| 55-56 | -.45492 | -.10089 | -.35403 |
| 56-57 | -1.54988 | -.58363 | -.96625 |
| 57-58 | -4.68197 | -1.32142 | -3.36055 |
| 58-59 | 3.79552 | 1.28066 | 2.51486 |
| 59-60 | -1.33435 | -.24944 | -1.08491 |
| 60-61 | .89861 | -.07368 | .97229 |
| 61-62 | -1.31813 | -.40736 | -.91077 |
| 62-63 | 2.43387 | .53557 | 1.89830 |
| 63-64 | -2.93210 | -.67272 | -2.25938 |
| 64-65 | .53373 | .14296 | .39077 |

36° N UPPER WATER- CONTINUED

| <u>STAT NO.</u> | <u>STAT TOTAL</u> | <u>SFC</u> | <u>NAC</u> |
|-----------------|-------------------|------------|------------|
| 65-66 | 1.62668 | .40517 | 1.22151 |
| 66-67 | -3.42892 | -1.16763 | -2.26129 |
| 67-68 | -2.47979 | -.57672 | -1.90307 |
| 68-69 | 1.30545 | .30962 | .99583 |
| 69-70 | 2.55489 | .67487 | 1.88002 |
| 70-71 | -2.67502 | -.73291 | -1.94211 |
| 71-72 | .38389 | .09011 | .29378 |
| 72-73 | 1.03943 | .48487 | .55456 |
| 73-74 | .10156 | .04385 | .05771 |
| 74-75 | -.39723 | -.21658 | -.18065 |
| 75-76 | -.20210 | -.20210 | 0.0 |
| 76-77 | .00605 | .00605 | 0.0 |
| TOTAL | 17.52581 | | |

36° N INTERMEDIATE WATER

| STAT NO. | STAT TOTAL | MIW | MED |
|----------|------------|----------|---------|
| 18-19 | 0.0 | 0.0 | 0.0 |
| 19-20 | .12119 | .12119 | 0.0 |
| 20-21 | -.33338 | -.33338 | 0.0 |
| 21-22 | .32365 | .32365 | 0.0 |
| 22-23 | -.72691 | -.72691 | 0.0 |
| 23-24 | -.25768 | -.25768 | 0.0 |
| 24-25 | .08429 | .08429 | 0.0 |
| 25-26 | -.13803 | -.13803 | 0.0 |
| 26-27 | -.09363 | -.09363 | 0.0 |
| 27-28 | .65239 | .65239 | 0.0 |
| 28-29 | .83370 | .83370 | 0.0 |
| 29-30 | 1.22073 | 1.22073 | 0.0 |
| 30-31 | .62257 | .62257 | 0.0 |
| 31-32 | -.39442 | -.39442 | 0.0 |
| 32-33 | .53909 | .53909 | 0.0 |
| 33-34 | -1.29913 | -1.29913 | 0.0 |
| 34-35 | -.10286 | -.10286 | 0.0 |
| 35-36 | .58265 | .58265 | 0.0 |
| 36-37 | .08138 | .08138 | 0.0 |
| 37-38 | .66444 | .66444 | 0.0 |
| 38-39 | -.61185 | -.61185 | 0.0 |
| 39-40 | -.68731 | -.68731 | 0.0 |
| 40-41 | -.49844 | -.49844 | 0.0 |
| 41-42 | -.00487 | -.00487 | 0.0 |
| 42-43 | -.00678 | -.00678 | 0.0 |
| 43-44 | -.25321 | -.25321 | 0.0 |
| 44-45 | .16978 | .16978 | 0.0 |
| 45-46 | -.07968 | -.07968 | 0.0 |
| 46-47 | -.57701 | -.57701 | 0.0 |
| 47-48 | -1.19516 | -1.19516 | 0.0 |
| 48-49 | 1.66396 | 1.66396 | 0.0 |
| 49-50 | .47279 | .47279 | 0.0 |
| 50-51 | -.42126 | -.42126 | 0.0 |
| 51-52 | .19264 | .20835 | -.01571 |
| 52-53 | -.26007 | -.27223 | .01226 |
| 53-54 | -.18331 | -.26018 | .07687 |
| 54-55 | -.68592 | -.56605 | -.11987 |
| 55-56 | -.17781 | -.11570 | -.06211 |
| 56-57 | 2.43134 | 2.31977 | .11157 |
| 57-58 | -.24287 | .33683 | -.57970 |
| 58-59 | .27212 | -.09360 | .36572 |
| 59-60 | .07708 | .27154 | -.19446 |
| 60-61 | -.80131 | -1.20673 | .40542 |
| 61-62 | .44901 | .56273 | -.11372 |
| 62-63 | .03679 | -.09849 | .13528 |
| 63-64 | .19234 | .21261 | -.02027 |
| 64-65 | -.78934 | -.69665 | -.09269 |

36° N INTERMEDIATE WATER- CONTINUED

| STAT NO. | STAT TOTAL | MIW | MED |
|----------|------------|----------|---------|
| 65-66 | -.89863 | -.72384 | -.17479 |
| 66-67 | -.06741 | -.23259 | .16518 |
| 67-68 | .31001 | .32971 | -.01970 |
| 68-69 | -1.35608 | -1.04260 | -.31348 |
| 69-70 | 1.45651 | 1.09457 | .36194 |
| 70-71 | 1.30968 | .80373 | .50595 |
| 71-72 | -1.05063 | -.69287 | -.35776 |
| 72-73 | -.50471 | -.50471 | 0.0 |
| 73-74 | .09813 | .09813 | 0.0 |
| 74-75 | .75777 | .75777 | 0.0 |
| 75-76 | 0.0 | 0.0 | 0.0 |
| 76-77 | 0.0 | 0.0 | 0.0 |
| TOTAL | .62068* | | |

* This total contains -.29564 mass units contributed by the bottom peripheral areas of the following stations: -.58417 units from station pair 72-73 ; .12257 units from station pair 73-74; and .16596 units from station pair 74-75.

36°N DEEP AND BOTTOM WATER

| <u>STAT NO.</u> | <u>STAT TOTAL (ALL WATER IS NAD)</u> |
|-----------------|----------------------------------------|
| 18-19 | 0.0 |
| 19-20 | .15680 |
| 20-21 | .53057 |
| 21-22 | -.07403 |
| 22-23 | 1.54217 |
| 23-24 | -.40487 |
| 24-25 | -.80570 |
| 25-26 | .45022 |
| 26-27 | -.36578 |
| 27-28 | -.45610 |
| 28-29 | -3.65122 |
| 29-30 | -12.05018 |
| 30-31 | -5.46189 |
| 31-32 | 5.64814 |
| 32-33 | -8.86169 |
| 33-34 | -10.55914 |
| 34-35 | -1.20714 |
| 35-36 | 2.96859 |
| 36-37 | -.69886 |
| 37-38 | 20.38948 |
| 38-39 | -15.61164 |
| 39-40 | 4.73402 |
| 40-41 | 8.69133 |
| 41-42 | -4.32715 |
| 42-43 | 9.73861 |
| 43-44 | -4.68205 |
| 44-45 | 13.24583 |
| 45-46 | -14.57470 |
| 46-47 | -15.52757 |
| 47-48 | -11.69013 |
| 48-49 | 17.12689 |
| 49-50 | 23.94253 |
| 50-51 | -9.62460 |
| 51-52 | 1.77155 |
| 52-53 | -1.05768 |
| 53-54 | -.95446 |
| 54-55 | -.21808 |
| 55-56 | 0.0 |
| 56-57 | 0.0 |
| 57-58 | .15434 |
| 58-59 | -.06792 |
| 59-60 | .30511 |
| 60-61 | -1.60163 |
| 61-62 | 1.24348 |
| 62-63 | -.43909 |
| 63-64 | 1.23135 |
| 64-65 | -.79077 |

36° N DEEP AND BOTTOM WATER- CONTINUED

| <u>STAT NO.</u> | <u>STAT TOTAL (ALL WATER IS NAD)</u> |
|-----------------|----------------------------------------|
| 65-66 | -3.64039 |
| 66-67 | .60408 |
| 67-68 | .12472 |
| 68-69 | -.81671 |
| 69-70 | .43942 |
| 70-71 | 5.44905 |
| 71-72 | -.72958 |
| 72-73 | 0.0 |
| 73-74 | 0.0 |
| 74-75 | 0.0 |
| 75-76 | 0.0 |
| 76-77 | 0.0 |
| TOTAL | -18.46247 |

40° N UPPER WATER

| STAT NO. | STAT TOTAL | SFC | NAC |
|----------|------------|----------|-----------|
| 218-219 | -.04788 | -.03583 | -.01205 |
| 219-220 | 5.21774 | 1.70588 | 3.51186 |
| 220-221 | -.96065 | .23393 | -1.19458 |
| 221-222 | -.19006 | -.18203 | -.00803 |
| 222-223 | 10.38285 | 3.00718 | 7.37567 |
| 223-224 | -7.67326 | -1.98048 | -5.69278 |
| 224-225 | .04960 | .06036 | -.01076 |
| 225-226 | -1.30019 | -.51937 | -.78082 |
| 226-227 | 27.83837 | 12.12414 | 15.71423 |
| 227-228 | -30.27794 | -7.30474 | -22.97320 |
| 228-229 | 2.27416 | 1.19430 | 1.07986 |
| 229-230 | -1.61474 | -.71312 | -.90162 |
| 230-231 | 14.09853 | 3.58525 | 10.51328 |
| 231-232 | -12.23265 | -4.72620 | -7.50645 |
| 232-233 | -5.21509 | -1.65181 | -3.56328 |
| 233-234 | 12.92696 | 4.48559 | 8.44137 |
| 234-235 | 20.89605 | 3.09161 | 17.80444 |
| 235-236 | -10.14042 | -1.40635 | -8.73407 |
| 236-237 | -11.44643 | -2.43838 | -9.00805 |
| 237-238 | 8.10690 | 1.43768 | 6.66922 |
| 238-239 | -6.48199 | -1.35873 | -5.12326 |
| 239-240 | 7.20672 | 1.21143 | 5.99529 |
| 240-241 | -5.81490 | -.95434 | -4.86056 |
| 241-242 | -.22323 | -.09638 | -.12685 |
| 242-243 | 1.50425 | .16422 | 1.34003 |
| 243-244 | 3.06300 | .36950 | 2.69350 |
| 244-245 | -2.47102 | -.48772 | -1.98330 |
| 245-246 | -.00699 | -.01844 | .01145 |
| 246-247 | -4.18647 | -.57803 | -3.60844 |
| 247-248 | 3.67331 | .48586 | 3.18745 |
| 248-249 | -.47383 | -.07633 | -.39750 |
| 249-250 | -1.01936 | -.19144 | -.82792 |
| 250-251 | -.55086 | -.32397 | -.22689 |
| 251-252 | -.28913 | -.00874 | -.28039 |
| 252-253 | -.46120 | -.09350 | -.36770 |
| 253-254 | .07594 | .05034 | .02560 |
| 254-255 | .03691 | .03691 | 0.0 |

TOTAL 14.43674*

* This total contains .16374 mass units contributed by the bottom peripheral area of stations 254-255 not included in the above summary.

40°N INTERMEDIATE WATER

| STAT NO. | STAT TOTAL | MIW | MED | NAI |
|----------|------------|----------|----------|---------|
| 218-219 | 0.0 | 0.0 | 0.0 | 0.0 |
| 219-220 | 2.62171 | 1.79335 | 0.0 | .82837 |
| 220-221 | -2.61501 | -.96222 | 0.0 | 1.65279 |
| 221-222 | .04745 | .04745 | 0.0 | 0.0 |
| 222-223 | 1.57072 | 1.57072 | 0.0 | 0.0 |
| 223-224 | -.99491 | -.99491 | 0.0 | 0.0 |
| 224-225 | .13776 | .13776 | 0.0 | 0.0 |
| 225-226 | -.22663 | -.22663 | 0.0 | 0.0 |
| 226-227 | 4.31605 | 2.44990 | 1.86615 | 0.0 |
| 227-228 | -4.49205 | -2.59960 | -1.89245 | 0.0 |
| 228-229 | .17960 | .17960 | 0.0 | 0.0 |
| 229-230 | -.19700 | -.19700 | 0.0 | 0.0 |
| 230-231 | 3.00265 | 2.29768 | .70497 | 0.0 |
| 231-232 | -2.63093 | -2.01226 | -.61867 | 0.0 |
| 232-233 | -1.94039 | -1.94039 | 0.0 | 0.0 |
| 233-234 | 3.13593 | 3.13593 | 0.0 | 0.0 |
| 234-235 | 4.81552 | 1.97984 | 2.83568 | 0.0 |
| 235-236 | -.83146 | -.83146 | 0.0 | 0.0 |
| 236-237 | -2.58909 | -1.54566 | -1.04343 | 0.0 |
| 237-238 | 1.54188 | -.01488 | 1.55676 | 0.0 |
| 238-239 | -1.03440 | -.30385 | -.73055 | 0.0 |
| 239-240 | 1.56927 | .90190 | .66737 | 0.0 |
| 240-241 | -1.28488 | -.75064 | -.53424 | 0.0 |
| 241-242 | .27035 | .08141 | .18894 | 0.0 |
| 242-243 | .37627 | -.07513 | .45140 | 0.0 |
| 243-244 | .26629 | -.26783 | .53412 | 0.0 |
| 244-245 | -.04355 | .22365 | -.26720 | 0.0 |
| 245-246 | -.02802 | .17271 | -.20073 | 0.0 |
| 246-247 | -.52602 | .18442 | -.71044 | 0.0 |
| 247-248 | .56730 | -.26282 | .83012 | 0.0 |
| 248-249 | -.43430 | -.55174 | .11744 | 0.0 |
| 249-250 | -.10412 | -.14524 | .04112 | 0.0 |
| 250-251 | -.07136 | -.01901 | -.05235 | 0.0 |
| 251-252 | .19781 | .23061 | -.03280 | 0.0 |
| 252-253 | -.23334 | -.37261 | .13927 | 0.0 |
| 253-254 | -.54460 | .34856 | -.89316 | 0.0 |
| 254-255 | 0.0 | 0.0 | 0.0 | 0.0 |

TOTAL 3.68615*

* This total contains -.10835 mass units contributed by the bottom peripheral areas of the following stations: -.09110 units from station pair 241-242; and -.01725 units from station pair 242-243.

40° N DEEP AND BOTTOM WATER

| <u>STAT NO.</u> | <u>STAT TCTAL (ALL WATER IS NAD)</u> |
|-----------------|----------------------------------------|
| 218-219 | 0.0 |
| 219-220 | 0.0 |
| 220-221 | .19147 |
| 221-222 | -.70677 |
| 222-223 | -9.27722 |
| 223-224 | 10.94129 |
| 224-225 | 1.58421 |
| 225-226 | -7.56315 |
| 226-227 | -15.61833 |
| 227-228 | 16.26318 |
| 228-229 | .73626 |
| 229-230 | 2.78113 |
| 230-231 | -9.35389 |
| 231-232 | 5.55042 |
| 232-233 | 8.00027 |
| 233-234 | -18.40148 |
| 234-235 | -17.95566 |
| 235-236 | 1.65467 |
| 236-237 | 22.21143 |
| 237-238 | -17.80792 |
| 238-239 | 9.91281 |
| 239-240 | -2.22031 |
| 240-241 | .13494 |
| 241-242 | 0.0 |
| 242-243 | 0.0 |
| 243-244 | -.50899 |
| 244-245 | 1.82697 |
| 245-246 | 1.47397 |
| 246-247 | 3.19672 |
| 247-248 | -4.81305 |
| 248-249 | -2.05300 |
| 249-250 | 1.68681 |
| 250-251 | .24704 |
| 251-252 | 2.36107 |
| 252-253 | -.69757 |
| 253-254 | -1.91959 |
| 254-255 | 0.0 |
| TOTAL | -18.142267 |

48° N UPPER WATER

| STAT NO. | STAT TOTAL | SFC | NAC |
|-----------|------------|----------|----------|
| 3509-3510 | -.00981 | -.00981 | 0.0 |
| 3510-3511 | -.15161 | -.15161 | 0.0 |
| 3511-3512 | -.53552 | -.53552 | 0.0 |
| 3512-3513 | .84282 | .84282 | 0.0 |
| 3513-3514 | 1.29535 | 1.29535 | 0.0 |
| 3514-3515 | -.67930 | -.67930 | 0.0 |
| 3515-3516 | -.71278 | -.71278 | 0.0 |
| 3516-3517 | -.36541 | -.36541 | 0.0 |
| 3517-3518 | 1.71756 | 1.71756 | 0.0 |
| 3518-3519 | 2.21573 | 2.21573 | 0.0 |
| 3519-3520 | -.55629 | -.55629 | 0.0 |
| 3520-3521 | -1.23456 | -1.23456 | 0.0 |
| 3521-3522 | 6.41815 | 3.99011 | 2.42804 |
| 3522-3523 | 17.03908 | 3.86525 | 13.17383 |
| 3523-3524 | -1.47752 | -.06010 | -1.41742 |
| 3524-3525 | -.54162 | -1.97081 | -5.57081 |
| 3525-3526 | -4.16548 | -1.04673 | -3.11875 |
| 3526-3527 | -6.94611 | -2.17632 | -4.76979 |
| 3527-3528 | 1.00725 | .40910 | .59815 |
| 3528-3529 | 1.03338 | .41257 | .62081 |
| 3529-3530 | 4.89086 | 1.56058 | 3.33028 |
| 3530-3531 | -5.94717 | -1.97482 | -3.97235 |
| 3531-3532 | 6.98923 | 2.04339 | 4.94584 |
| 3532-3533 | 1.81258 | .29875 | 1.51383 |
| 3533-3534 | -.35963 | -.08926 | -.27037 |
| 3534-3535 | -3.78857 | -.82127 | -2.96730 |
| 3535-3536 | 2.47470 | .65940 | 1.81530 |
| 3536-3537 | -.90544 | -.33530 | -.57014 |
| 3537-3538 | -1.86396 | -.56325 | -1.30071 |
| 3538-3539 | 3.68074 | .88576 | 2.79498 |
| 3539-3540 | -3.19582 | -.72731 | -2.46851 |
| 3540-3541 | 1.56617 | .33683 | 1.22934 |
| 3541-3542 | -.17904 | -.05062 | -.12842 |
| 3542-3543 | .47447 | .13179 | .34268 |
| 3543-3544 | .03057 | .00643 | .02414 |
| 3544-3545 | -.03639 | -.03358 | -.00281 |
| 3545-3546 | -.00770 | -.00770 | 0.0 |
| 3546-3547 | .00585 | .00585 | 0.0 |
| 3547-3548 | .00289 | .00289 | 0.0 |
| TOTAL | 12.83765 | | |

48° N INTERMEDIATE WATER

| STAT NO. | STAT TOTAL | MIW | MED | NAI |
|-----------|------------|----------|---------|---------|
| 3509-3510 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3510-3511 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3511-3512 | -.67318 | -.05702 | 0.0 | -.61616 |
| 3512-3513 | .41689 | .10413 | 0.0 | .31276 |
| 3513-3514 | 1.10080 | .53201 | 0.0 | .56879 |
| 3514-3515 | -.49992 | -.22803 | 0.0 | -.27189 |
| 3515-3516 | -.44236 | -.28556 | 0.0 | -.15680 |
| 3516-3517 | -.17099 | -.10245 | 0.0 | -.06854 |
| 3517-3518 | .69397 | .18753 | 0.0 | .50644 |
| 3518-3519 | 3.42882 | 2.96343 | 0.0 | .46539 |
| 3519-3520 | -.20883 | -.17198 | 0.0 | -.03685 |
| 3520-3521 | -1.68176 | -1.03406 | 0.0 | -.64770 |
| 3521-3522 | 2.82592 | 1.76582 | 0.0 | 1.06010 |
| 3522-3523 | 1.79552 | 1.79552 | 0.0 | 0.0 |
| 3523-3524 | .42217 | .42217 | 0.0 | 0.0 |
| 3524-3525 | -.83182 | -.83182 | 0.0 | 0.0 |
| 3525-3526 | -.97029 | -.97029 | 0.0 | 0.0 |
| 3526-3527 | -1.43363 | -1.43363 | 0.0 | 0.0 |
| 3527-3528 | .67024 | .67024 | 0.0 | 0.0 |
| 3528-3529 | -.67521 | -.67521 | 0.0 | 0.0 |
| 3529-3530 | 1.37737 | 1.37737 | 0.0 | 0.0 |
| 3530-3531 | -1.26854 | -1.26854 | 0.0 | 0.0 |
| 3531-3532 | .15823 | .15823 | 0.0 | 0.0 |
| 3532-3533 | -.44624 | -.44624 | 0.0 | 0.0 |
| 3533-3534 | .11933 | .11933 | 0.0 | 0.0 |
| 3534-3535 | -.35591 | -.35591 | 0.0 | 0.0 |
| 3535-3536 | -.10297 | -.31489 | .21192 | 0.0 |
| 3536-3537 | .19792 | .35745 | -.15953 | 0.0 |
| 3537-3538 | -.45640 | .02806 | -.48446 | 0.0 |
| 3538-3539 | -.31704 | -1.01762 | .70058 | 0.0 |
| 3539-3540 | .18956 | .55299 | -.36343 | 0.0 |
| 3540-3541 | 1.09598 | -.11268 | 1.0191 | 0.0 |
| 3541-3542 | -.07626 | -.06174 | -.01452 | 0.0 |
| 3542-3543 | -.42285 | -.34850 | -.07435 | 0.0 |
| 3543-3544 | .08868 | -.00186 | .09054 | 0.0 |
| 3544-3545 | .15415 | .15415 | 0.0 | 0.0 |
| 3545-3546 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3546-3547 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3547-3548 | 0.0 | 0.0 | 0.0 | 0.0 |

TOTAL 3.80428*

* This total contains .10294 mass units contributed by the bottom peripheral areas of the following stations: .02537 units from station pair 3543-3544; .05809 units from station pair 3544-3545; and .01948 units from station pair 3545-3546.

48°N DEEP AND BOTTOM WATER

| STAT NO. | STAT TOTAL (ALL WATER IS NAD) |
|-----------|---------------------------------|
| 3509-3510 | 0.0 |
| 3510-3511 | 0.0 |
| 3511-3512 | .85412 |
| 3512-3513 | -.16718 |
| 3513-3514 | -2.04567 |
| 3514-3515 | .11280 |
| 3515-3516 | 1.29288 |
| 3516-3517 | 1.45585 |
| 3517-3518 | -3.58715 |
| 3518-3519 | -8.12712 |
| 3519-3520 | -3.08709 |
| 3520-3521 | -8.08643 |
| 3521-3522 | 1.70124 |
| 3522-3523 | -17.55530 |
| 3523-3524 | 5.78760 |
| 3524-3525 | 9.01827 |
| 3525-3526 | 7.22985 |
| 3526-3527 | 3.98344 |
| 3527-3528 | 1.39936 |
| 3528-3529 | -.19862 |
| 3529-3530 | -2.90514 |
| 3530-3531 | 1.78800 |
| 3531-3532 | -4.91310 |
| 3532-3533 | -1.72700 |
| 3533-3534 | 1.75836 |
| 3534-3535 | 1.44476 |
| 3535-3536 | -10.93589 |
| 3536-3537 | 3.68454 |
| 3537-3538 | 5.27132 |
| 3538-3539 | -11.87332 |
| 3539-3540 | 7.57365 |
| 3540-3541 | 2.37592 |
| 3541-3542 | 3.08240 |
| 3542-3543 | -1.24236 |
| 3543-3544 | 0.0 |
| 3544-3545 | 0.0 |
| 3545-3546 | 0.0 |
| 3546-3547 | 0.0 |
| 3547-3548 | 0.0 |
| TOTAL | -16.63701 |

APPENDIX B

MASS, SALT, AND HEAT TRANSPORT ESTIMATES FOR PERIPHERAL AREAS

In calculating the estimated values of mass, salt, and heat transport for the peripheral areas the following procedure was followed.

Temperature and salinity information was obtained for the area and month of interest from the Fleet Numerical Weather Central's "HYDAT" program. The program output supplied all available temperature and salinity data for the area and month requested as well as computing temperature statistics. If no data were found to exist for the desired area, the closest station's temperature and salinity data were considered representative of the entire area (this occurred for the 8°N western peripheral area and the 32°N eastern peripheral area).

Next, the monthly average surface current velocity was taken from the "Pilot Chart of the North Atlantic Ocean" for the month of interest. This value was assumed to equal the geostrophic surface current velocity. A linear decrease in velocity was assumed with zero velocity at the bottom. Therefore, a value of one-half the surface current velocity was considered to equal the mean current velocity for the entire area.

The value of average current velocity was then multiplied by the peripheral area (Table II) and the average density value of 1.02395 gm/cm³ (Greeson, 1974), determining the mass transport. This value was in turn multiplied by the mean temperature and salinity values for the peripheral area, determining the salt and heat transport.

The results of this study are contained on the following pages.

I. 48°N

A. WEST AREA

$$T = -.23^{\circ}\text{C}$$

$$S = 33.26 \text{ ‰}$$

$$\text{AREA} = 2.35 \times 10^{11} \text{ cm}^2$$

$$\text{VEL} = -10.16 \text{ cm/sec}$$

$$\text{MASS T} = -2.44 \times 10^{12} \text{ gm/sec}$$

$$\text{SALT T} = -81.31 \times 10^{12} \text{ ‰/sec}$$

$$\text{HEAT T} = -667.25 \times 10^{12} \text{ cal/sec}$$

$$\text{TOTAL MASS TRANS} = -1.14 \times 10^{12} \text{ gm/sec}$$

$$\text{TOTAL SALT TRANS} = -35.07 \times 10^{12} \text{ ‰/sec}$$

$$\text{TOTAL HEAT TRANS} = -270.27 \times 10^{12} \text{ cal/sec}$$

B. EAST AREA

$$T = 11.35^{\circ}\text{C}$$

$$S = 35.56 \text{ ‰}$$

$$\text{AREA} = 1.25 \times 10^{11} \text{ cm}^2$$

$$\text{VEL} = 10.16 \text{ cm/sec}$$

$$\text{MASS T} = 1.30 \times 10^{12} \text{ gm/sec}$$

$$\text{SALT T} = 46.24 \times 10^{12} \text{ ‰/sec}$$

$$\text{HEAT T} = 369.98 \times 10^{12} \text{ cal/sec}$$

II. 40°N (Values taken from Greeson, 1974, Table IV)

A. WEST AREA

$$\text{MASS T} = -6.439 \times 10^{12} \text{ gm/sec}$$

$$\text{SALT T} = -213.540 \times 10^{12} \text{ ‰/sec}$$

$$\text{HEAT T} = -1842.942 \times 10^{12} \text{ cal/sec}$$

$$\text{TOTAL MASS TRANS} = -6.567 \times 10^{12} \text{ gm/sec}$$

$$\text{TOTAL SALT TRANS} = -218.129 \times 10^{12} \text{ ‰/sec}$$

$$\text{TOTAL HEAT TRANS} = -1874.968 \times 10^{12} \text{ cal/sec}$$

B. EAST AREA

$$\text{MASS T} = -.128 \times 10^{12} \text{ gm/sec}$$

$$\text{SALT T} = -4.589 \times 10^{12} \text{ ‰/sec}$$

$$\text{HEAT T} = -32.026 \times 10^{12} \text{ cal/sec}$$

III. 36°N

A. WEST AREA

$$T = 19.82^{\circ}\text{C}$$

$$S = 36.09 \text{ ‰}$$

$$\text{AREA} = 6 \times 10^{10} \text{ cm}^2$$

$$\text{VEL} = -20.3 \text{ cm/sec}$$

$$\text{MASS T} = -1.24 \times 10^{12} \text{ gm/sec}$$

$$\text{SALT T} = -45.01 \times 10^{12} \text{ ‰/sec}$$

$$\text{HEAT T} = -365.40 \times 10^{12} \text{ cal/sec}$$

$$\text{TOTAL MASS TRANS} = -1.37 \times 10^{12} \text{ gm/sec}$$

$$\text{TOTAL SALT TRANS} = -49.68 \times 10^{12} \text{ ‰/sec}$$

$$\text{TOTAL HEAT TRANS} = -402.65 \times 10^{12} \text{ cal/sec}$$

B. EAST AREA

$$T = 13.27^{\circ}\text{C}$$

$$S = 35.96 \text{ ‰}$$

$$\text{AREA} = 1 \times 10^{10} \text{ cm}^2$$

$$\text{VEL} = -12.7 \text{ cm/sec}$$

$$\text{MASS T} = -.13 \times 10^{12} \text{ gm/sec}$$

$$\text{SALT T} = -4.67 \times 10^{12} \text{ ‰/sec}$$

$$\text{HEAT T} = -37.25 \times 10^{12} \text{ cal/sec}$$

IV. 32°N

A. WEST AREA

$$T = 17.87^{\circ}\text{C}$$

$$S = 35.96 \text{ ‰}$$

$$\text{AREA} = 6 \times 10^{10} \text{ cm}^2$$

$$\text{VEL} = -20.3 \text{ cm/sec}$$

$$\text{MASS } T = -1.25 \times 10^{12} \text{ gm/sec}$$

$$\text{SALT } T = -44.85 \times 10^{12} \text{ ‰/sec}$$

$$\text{HEAT } T = -362.96 \times 10^{12} \text{ cal/sec}$$

$$\text{TOTAL MASS TRANS} = -1.64 \times 10^{12} \text{ gm/sec}$$

$$\text{TOTAL SALT TRANS} = -59.04 \times 10^{12} \text{ ‰/sec}$$

$$\text{TOTAL HEAT TRANS} = -476.24 \times 10^{12} \text{ cal/sec}$$

B. EAST AREA

$$T = 17.21^{\circ}\text{C}$$

$$S = 36.38 \text{ ‰}$$

$$\text{AREA} = 3 \times 10^{10} \text{ cm}^2$$

$$\text{VEL} = -12.7 \text{ cm/sec}$$

$$\text{MASS } T = -.39 \times 10^{12} \text{ gm/sec}$$

$$\text{SALT } T = -14.19 \times 10^{12} \text{ ‰/sec}$$

$$\text{HEAT } T = -113.28 \times 10^{12} \text{ cal/sec}$$

V. 24°N

A. WEST AREA

$$T = 14.39^{\circ}\text{C}$$

$$S = 35.77 \text{ ‰}$$

$$\text{AREA} = 5 \times 10^9 \text{ cm}^2$$

$$\text{VEL} = 12.7 \text{ cm/sec}$$

$$\text{MASS } T = .065 \times 10^{12} \text{ gm/sec}$$

$$\text{SALT } T = 2.33 \times 10^{12} \text{ ‰/sec}$$

$$\text{HEAT } T = 18.69 \times 10^{12} \text{ cal/sec}$$

$$\text{TOTAL MASS TRANS} = -.71 \times 10^{12} \text{ gm/sec}$$

$$\text{TOTAL SALT TRANS} = -25.83 \times 10^{12} \text{ ‰/sec}$$

$$\text{TOTAL HEAT TRANS} = -207.44 \times 10^{12} \text{ cal/sec}$$

B. EAST AREA

$$T = 18.62^{\circ}\text{C}$$

$$S = 36.33 \text{ ‰}$$

$$\text{AREA} = 6 \times 10^{10} \text{ cm}^2$$

$$\text{VEL} = -12.7 \text{ cm/sec}$$

$$\text{MASS } T = .78 \times 10^{12} \text{ gm/sec}$$

$$\text{SALT } T = -28.16 \times 10^{12} \text{ ‰/sec}$$

$$\text{HEAT } T = -226.13 \times 10^{12} \text{ cal/sec}$$

VI. 16°N

A. WEST AREA

No peripheral area associated with this section.

$$\text{TOTAL MASS TRANS} = 0.0$$

$$\text{TOTAL SALT TRANS} = 0.0$$

$$\text{TOTAL HEAT TRANS} = 0.0$$

B. EAST AREA

No net meridional transports in this section. Peripheral area is characterized by opposing currents of equal magnitude.

VII. 8°N

A. WEST AREA

$$T = 14.79^{\circ}\text{C}$$

$$S = 34.99 \text{ }^{\circ}/_{\text{00}}$$

$$\text{AREA} = 2 \times 10^{10} \text{ cm}^2$$

$$\text{VEL} = 25.4 \text{ cm/sec}$$

$$\text{MASS T} = 0.52 \times 10^{12} \text{ gm/sec}$$

$$\text{SALT T} = 18.2 \times 10^{12} \text{ }^{\circ}/_{\text{00}}/\text{sec}$$

$$\text{HEAT T} = 149.78 \times 10^{12} \text{ cal/sec}$$

$$\text{TOTAL MASS TRANS} = 0.52 \times 10^{12} \text{ gm/sec}$$

$$\text{TOTAL SALT TRANS} = 18.2 \times 10^{12} \text{ }^{\circ}/_{\text{00}}/\text{sec}$$

$$\text{TOTAL HEAT TRANS} = 149.78 \times 10^{12} \text{ cal/sec}$$

B. EAST AREA

No net meridional transport
in this area. Peripheral
area is characterized by
zonal currents.

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